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Drift from field crop sprayers:

The influence of spray application technology determined using indirect and direct drift assessment means

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door

David NUYTTENS

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Voorwoord - Preface

Eindelijk… het is klaar… mijn boekje… mijn doctoraat…

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David

Samenvatting

De laatste jaren is de bezorgdheid over het gebruik van gewasbeschermingsmiddelen in land- en tuinbouw sterk toegenomen. Eén van de problemen is het wegdriften van gewasbeschermingsmiddelen tijdens of net na hun toepassing naar plaatsen buiten het behandelde perceel met mogelijke gevolgen zoals schade aan buurgewassen, contaminatie van oppervlaktewaters, gezondheidsrisico's voor mens en dier en productverlies.

Het hoofdobjectief van deze studie was het bepalen van het effect van de spuittechniek op de hoeveelheid drift bij veldspuiten. Hiervoor werden directe en indirecte drift-meettechnieken ontwikkeld, toegepast en vergeleken, namelijk PDPA lasermetingen, windtunnelmetingen en drift-veldmetingen. Er werd een referentietechniek gebruikt waarmee alle andere onderzochte spuittechnieken vergeleken werden. Deze referentie was gedefinieerd als een standaard horizontale spuitboom met een boomhoogte en dopafstand van 0.50 m, ISO 03 standaard spleetdoppen bij een druk van 3.0 bar en een rijsnelheid van 8.0 $km.u^{-1}$. Naast deze referentietechniek werden nog verschillende andere spuittechnieken getest om het effect na te gaan van doptype (standaard spleetdop, driftreducerende spleetdop, luchtmengdop), dopgrootte (ISO 02, 03, 04 en 06), rijsnelheid (4, 6, 8 en 10 $km.u^{-1}$), boomhoogte (0.30, 0.50 en 0.75 m) en het gebruik van luchtondersteuning.

Met de ontwikkelde *PDPA laseropstelling* werden zowel druppelgroottes als -snelheden opgemeten. Deze opstelling bestond uit een spuitgroep, een 3D-geautomatiseerde positioneertafel en een Aerometrics PDPA laser in een geklimatiseerde ruimte.
Windtunnelmetingen, uitgevoerd in het Silsoe Research Institute (SRI), werden gebruikt om de *airborne* en de *fallout* vloeistofdeposities te bepalen van een statische spuitdop blootgesteld aan een constante windsnelheid. Meetresultaten van de verschillende spuittechnieken werden gebruikt om hun driftpotentieel-reductiepercentage (*DPRP*) te berekenen volgens drie benaderingen. Deze *DPRP* waarden drukken de reductie uit (in percent) van het driftpotentieel van een bepaalde techniek t.o.v. de referentietechniek. Bij de eerste benadering werd het eerste moment van de *airborne* depositiecurve ($DPRP_{V1}$) berekend. Bij de tweede en derde benadering werd gebruik gemaakt van de oppervlaktes onder de gemeten *airborne* ($DPRP_{V2}$) en *fallout* ($DPRP_H$) depositiecurves .
Tijdens de *veldmetingen* werd depositiedrift bemonsterd op 24 posities windafwaarts tot op 20 m van de bespoten zone door middel van collectoren en een fluorescerende tracer. De weersomstandigheden werden continu geregistreerd.
Met de referentietechniek werden 27 veld-drifmetingen uitgevoerd bij verschillende klimatologische omstandigheden. Deze metingen demonstreerden de belangrijke invloed van de weersomstandigheden op de hoeveelheid depositiedrift. Een niet-lineaire drift-predictievergelijking werd opgesteld en gevalideerd waarmee de hoeveelheid depositiedrift kan voorspeld worden voor de referentietechniek als functie van de driftafstand, de gemiddelde windsnelheid op een hoogte van 3.25 m en de gemiddelde temperatuur en relatieve vochtigheid. Deze vergelijking toonde aan dat de hoeveelheid depositiedrift stijgt bij een toename van de windsnelheid en de temperatuur en bij een afname van de absolute vochtigheid en benadrukt het belangrijk effect van temperatuur en relatieve vochtigheid op de hoeveelheid drift. Ze werd gebruikt om de veldmetingen met

verschillende spuittechnieken bij variërende weersomstandigheden te vergelijken met de referentietechniek via de berekening van hun driftreductiepotentieel (DRP_t).
In totaal werden 162 PDPA lasermetingen, 51 windtunnelmetingen en 108 velddriftmetingen uitgevoerd. Op basis van deze metingen werden druppelgrootte- en druppelsnelheidskarakteristieken, *DPRP* en DRP_t waarden berekend en vergeleken voor de verschillende spuittechnieken om het effect van spuittechniek op depositiedrift na te gaan en om de mogelijkheden van de verschillende drift-meettechnieken te evalueren.

De PDPA lasermetingen toonden aan dat druppelgroottes varieerden van slechts enkele tot bijna 1000 micrometer en druppelsnelheden van ongeveer 0 $m.s^{-1}$ tot 16 $m.s^{-1}$. Druppelgroottes en -snelheden waren bovendien onderling gerelateerd en beiden werden beïnvloed door zowel doptype, -grootte en spuitdruk. Druppelsnelheden op een afstand van 0.50 m van de spuitdop werden voornamelijk bepaald door hun ejectiesnelheid en hun grootte. Kleinere druppels namen sneller af in snelheid ten gevolge van de luchtweerstand in vergelijking met grotere druppels. Daarnaast varieerden druppelsnelheden ook voor één en dezelfde druppelgrootte afhankelijk van doptype en -grootte door variaties in ejectiesnelheden. Met deze opstelling was het mogelijk om een grote hoeveelheid nuttige en herhaalbare druppelgrootte- en druppelsnelheidsdata te genereren onder gecontroleerde condities. Uit de vergelijking met andere studies, bleek bovendien het belang van referentiedoppen om spuitnevels te classificeren omwille van de aanzienlijke variatie in absolute meetresultaten door verschillen in meetprotocol, -toestel en -instellingen.

Standaard spleetdoppen produceerden het fijnste druppelgroottespectrum gevolgd door de driftreducerende en de luchtmengdoppen wat resulteerde in significante verschillen in het aandeel kleine, driftgevoelige druppels (bv. V_{100}, V_{200}) en in verschillende andere druppelgroottekarakteristieken zoals $D_{v0.5}$, *RSF*, D_{10}, enz. Het effect van doptype op de druppelgroottes was het meest uitgesproken voor de kleinere ISO dopgroottes. Voor éénzelfde druppelgrootte waren de druppelsnelheden het grootst voor de standaard spleetdoppen gevolgd door de driftreducerende en de luchtmengdoppen omwille van variaties in ejectiesnelheden veroorzaakt door verschillen in de bouw en het werkingsprincipe van de verschillende doptypes. Globaal bekeken zijn de druppelsnelheden echter het hoogst voor de luchtmengdoppen gevolgd door de driftreducerende en de standaard spleetdoppen - opnieuw voor éénzelfde ISO dopgrootte en spuitdruk - omwille van hun grovere en dus snellere druppels. Dit betekent dat de druppelgrootte een belangrijkere invloed heeft dan de ejectiesnelheid op de druppelsnelheden op 0.50 m. Windtunnel- en veldmetingen toonden eveneens aan dat - voor éénzelfde dopgrootte en spuitdruk - DRP_t en *DPRP* waarden het hoogst waren voor de luchtmengdoppen, gevolgd door de driftreducerende en de standaard spleetdoppen. Opnieuw waren de verschillen het meest uitgesproken voor de kleinere ISO dopgroottes.

Naast het effect van doptype bleek ook dat - voor éénzelfde doptype en spuitdruk - grotere ISO dopgroottes een grover druppelgroottespectrum produceerden met een kleiner aandeel kleine druppeltjes. Dit effect is het grootst bij de standaard spleetdoppen gevolgd door de driftreducerende spleetdoppen en is minder uitgesproken bij de luchtmengdoppen. Grotere doppen produceerden bovendien ook snellere druppels op een dopafstand van 0.50 m. Dit werd enerzijds veroorzaakt door het feit dat grotere druppels ook sneller zijn en anderzijds doordat ejectiesnelheden groter zijn bij grotere ISO dopgroottes. Deze resultaten reflecteerden zich opnieuw in de resultaten van de windtunnel- en de veldmetingen. Hoe groter de ISO dopgrootte, hoe hoger de *DPRP* en de DRP_t waarden voor de standaard en de driftreducerende spleetdoppen bij een constante spuitdruk. Voor de luchtmengdoppen was het effect van dopgrootte minder uitgesproken maar de *DPRP* and DRP_t waarden waren steeds hoog met de hoogste waarden voor de ISO 03 luchtmengdoppen.

Om het effect van de spuitdruk op drift en driftgevoeligheid na te gaan, werden een beperkte reeks metingen uitgevoerd met de ISO 03 standaard spleetdop bij drukken van 2.0 tot 4.0 bar. Betreffende de druppelsnelheden bleek een daling van de druk (binnen dit drukinterval) enkel de snelste druppelsnelheidskarakteristieken (v_{vol75} and v_{vol90}) significant te doen dalen. Niettegenstaande een daling van de druk van 3.0 tot 2.0 bar geen significant effect had op de gemeten druppelgroottes, resulteerde deze drukdaling in de windtunnel wel in een stijging van de *airborne* en de *fallout* vloeistofdeposities wat kan toegeschreven worden aan de gewijzigde druppelsnelheden. In tegenstelling tot deze resultaten, werden bij de drift-veldmetingen lagere driftwaarden gevonden bij een afname van de spuitdruk van 3.0 tot 2.0 bar. Een stijging van de druk van 3.0 tot 4.0 bar resulteerde wel in een daling van de druppelgroottes maar dit effect was beperkt in vergelijking met het effect van doptype of -grootte. In het veld werd een stijging van de hoeveelheid drift gevonden onder invloed van deze drukstijging.

Naast doptype, dopgrootte en spuitdruk - parameters die een invloed hebben op de druppeleigenschappen - hadden ook rijsnelheid en spuitboomhoogte een effect op de hoeveelheid depositiedrift. Uit de veld- en de windtunnelmetingen bleek het verlagen van de spuitboom een goede techniek te zijn om het driftrisico te reduceren onder voorwaarde dat een uniform spuitbeeld behouden blijft. Lagere driftwaarden werden opgemeten bij lagere rijsnelheden van 4 of 6 $km.u^{-1}$ in vergelijking met de referentiesnelheid van 8 $km.u^{-1}$. Tussen een verhoogde rijsnelheid van 10 $km.u^{-1}$ en de referentiesnelheid werd geen statistisch significant verschil vastgesteld.

Het gebruik van luchtondersteuning was driftreducerend in combinatie met zowel de Hardi ISO F 110 02, de F 110 03 als de LD 110 02 doppen met driftreductiefactoren α_d van respectievelijk 2.08, 1.77 en 1.53. In combinatie met de LD 110 03 doppen, werd echter geen statistisch significant driftreducerend effect waargenomen. De resultaten van de veldmetingen in combinatie met de PDPA lasermetingen toonden aan dat het driftreducerende effect van luchtondersteuning toeneemt naarmate het druppelgroottespectrum fijner is.

Bij het vergelijken van de drie verschillende drift-meettechnieken, bleken zowel de druppelgrootte- als de druppelsnelheidskarakteristieken gecorreleerd te zijn met zowel de DRP_t waarden, afkomstig van de drift-veldmetingen, als met de *DPRP* waarden, afkomstig van de windtunnelmetingen. Algemeen bekeken stegen DRP_t en *DPRP* met toenemende waarden van druppelgroottes en -snelheden en met dalende waarden van het aandeel kleine druppels in de spuitnevel.

Het volumetrisch aandeel van druppeltjes kleiner dan 200 µm in diameter (V_{200}) was de beste individuele indicator voor de hoeveelheid depositiedrift in het veld met een R^2 waarde van 0.90. Naast V_{200} waren ook de druppelgroottekarakteristieken V_{50}, V_{75}, V_{100}, V_{150} en V_{250} en de snelheidsspreidingsfactor (*VSF*) sterk gecorreleerd met DRP_t. Hoe hoger *VSF*, of hoe minder uniform de druppelsnelheidsverdeling, hoe lager de DRP_t waarde. Dit toont opnieuw het verband aan tussen druppelgroottes en -snelheden.

Bij de windtunnelmetingen waren de verschillende individuele druppelgrootte-karakteristieken het best gecorreleerd met $DPRP_H$ gevolgd door $DPRP_{V2}$ en $DPRP_{V1}$, terwijl het omgekeerde gevonden werd voor de druppelsnelheidskarakteristieken. $DPRP_H$ was het best gecorreleerd met de druppelgroottekarakteristieken V_{100}, V_{150} and V_{200} met telkens een R^2 waarde van 0.92 terwijl $DPRP_{V2}$ het best gecorreleerd was met de druppelsnelheidskarakteristiek *VSF* (R^2= 0.90) en $DPRP_{V1}$ met v_{vol10} (R^2= 0.86). Dit bevestigt opnieuw de belangrijke relatie tussen druppelsnelheden en -groottes en geeft bovendien aan dat druppelgroottekarakteristieken sterker gecorreleerd zijn met *fallout* deposities in vergelijking met *airborne* deposities terwijl het omgekeerde gevonden werd voor de druppelsnelheidskarakteristieken.

Tussen DRP_t waarden van de veldmetingen en *DPRP* waarden van de windtunnelmetingen werd een vrij goede overeenkomst gevonden. De beste correlatie werd gevonden voor $DPRP_H$ (R^2= 0.88) gevolgd door $DPRP_{V2}$ (R^2=0.81) en $DPRP_{V1}$ (R^2=0.66). Bovendien werden op basis van beide drift-meettechnieken (DRP_t en *DPRP*) gelijkaardige trends gevonden betreffende het effect van doptype en -grootte, boomhoogte en spuitdruk niettegenstaande absolute resultaten in beperkte mate konden variëren voornamelijk voor variërende spuitdrukken en spuithoogtes. Dit betekent dat de windtunnelbenadering waarbij de oppervlakte onder de depositiecurve bepaald wordt, het best geschikt is om de in het veld gemeten DRP_t waarden te benaderen. Anderzijds is de andere indirecte drift-meettechniek waarbij V_{200} waarden opgemeten werden met de PDPA laser, minstens even geschikt om DRP_t waarden te benaderen als de windtunnelmethode waarbij $DPRP_H$ waarden berekend werden en zelfs beter geschikt dan de windtunnelmethoden waarbij $DPRP_{V1}$ en $DPRP_{V2}$ bepaald werden. Met de PDPA laser is het echter enkel mogelijk om het effect van doptype en -grootte en spuitdruk te evalueren terwijl in de windtunnel ook het effect van de dophoogte kan geëvalueerd worden. Met beide indirecte drift-meettechnieken is het moeilijk om het effect van rijsnelheid of luchtondersteuning na te gaan, wat wel mogelijk is tijdens de drift-veldmetingen. Daarnaast zijn veldmetingen noodzakelijk om werkelijke driftwaarden te bekomen voor veldspuiten bij een brede waaier aan werkcondities maar dergelijke metingen zijn tijdrovend en kostelijk.

In deze studie werd een meetprotocol en een drift-predictievergelijking opgesteld om de interpretatie van driftdata te verbeteren en te versnellen. Met deze drift-predictievergelijking in combinatie met de DRP_t waarde van een bepaalde techniek, is het mogelijk om driftwaarden te voorspellen voor een brede waaier aan weersomstandigheden. Met de indirecte drift-meettechnieken (windtunnel en PDPA laser) kunnen metingen met verschillende spuittechnieken uitgevoerd worden bij herhaalbare omstandigheden en beide technieken zijn geschikt om relatieve driftrisicostudies uit te voeren. Bovendien kan op basis van $DPRP_H$ of V_{200} - afkomstig van deze indirecte meettechnieken - een goede inschatting gemaakt worden van DRP_t. Hiermee is het opnieuw mogelijk om in functie van de weersomstandigheden een realistische schatting te maken van de te verwachten driftwaarden bij een rijsnelheid van 8 $km.u^{-1}$ en een boomhoogte van 0.50 m.

Een ruime database met druppelkarakteristieken, windtunnel *fallout* en *airborne* deposities en werkelijke driftwaarden voor verschillende spuittechnieken werd opgesteld met extra informatie betreffende het effect van meteorologische condities. De resultaten waren in relatief goede overeenstemming met de resultaten van andere studies niettegenstaande vergelijken moeilijk is omwille van verschillen in o.a. spuittechnieken, proefopzet, tracer, weersomstandigheden en gewascondities. Vandaar het belang om in de toekomst dieper in te gaan op de relatie tussen directe en indirecte drift-meettechnieken en om alle internationaal beschikbare databases samen te brengen.

Abstract

Society's preoccupation with the use of plant protection products has increased significantly during the last few years. When pesticides are applied some of the spray may move beyond the intended area to undesirable areas which might have consequences such as damage to sensitive adjoining crops, water contamination, health risks to animals and people and a lower dose than intended on the target field.

The general objective of this research was to investigate the influence of spray application technology on the amount of spray drift from field crop sprayers. Therefore, indirect and direct drift assessment means were used and compared namely PDPA laser, wind tunnel and field drift measurements. A reference spraying was used for a comparative assessment of the different evaluated spray application techniques. This reference spraying was defined as a standard horizontal boom sprayer with a spray boom height and nozzle distance of 0.50 m, ISO 03 standard flat fan nozzles at a pressure of 3.0 bar and a driving speed of 8 km.h^{-1}. Besides this reference spraying, different other spray application techniques were tested to assess the effect of nozzle type (standard flat fan, low-drift, air inclusion), nozzle size (ISO 02, 03, 04 and 06), spray pressure (2.0, 3.0 and 4.0 bar), driving speed (4, 6, 8 and 10 km.h^{-1}), spray boom height (0.30, 0.50 and 0.75 m) and air assistance.

The developed *PDPA laser measuring set-up* is composed of a spray unit, a three-dimensional automated positioning system and an Aerometrics PDPA laser system in a controlled climate room which measures droplet size and velocity characteristics using a well-defined measuring protocol.
Wind tunnel measurements, performed in Silsoe Research Institute (SRI), were used to measure airborne and fallout spray volumes under directly comparable and repeatable conditions for single and static nozzles. Based on these measurements, drift potential reduction percentages (*DPRP*), expressing the percentage reduction of the drift potential compared with the reference spraying, were calculated following three approaches. The first approach was based on the calculation of the first moment of the airborne spray profile ($DPRP_{V1}$). In the second and third approach, the surface under the measured airborne ($DPRP_{V2}$) and fallout ($DPRP_{H}$) deposit curve were used.
For the *field measurements*, sedimenting spray drift was determined by sampling in a downwind area at 24 different positions using horizontal drift collectors in combination with a fluorescent tracer with measurements up to 20 m from the directly sprayed zone. Meteorological conditions were continuously monitored.
Based on 27 drift experiments with the reference spraying at various environmental conditions the important effect of atmospheric conditions on the amount of near-field sedimenting spray drift was demonstrated and quantified. A non-linear drift prediction equation was set up and validated, to predict the expected magnitude of drift for the reference spray application as a function of drift distance, average wind speed at a height of 3.25 m, average temperature and absolute humidity. This equation shows that decreasing wind speed and temperature and increasing absolute humidity decreases the amount of sedimenting spray drift and stresses the important effect of air humidity and

temperature. This equation was used to compare the drift results of the different spraying techniques under various weather conditions with the reference spraying by calculating their drift reduction potential (DRP_t).

In total, 162 PDPA laser measurements, 51 wind tunnel experiments and 108 field drift experiments were performed. From these measurements, droplet size and velocity characteristics at a nozzle distance of 0.50 m, drift potential reduction percentages ($DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$) and drift reduction potentials (DRP_t) were determined and compared for the different spray application techniques to investigate their effect on the amount of near-field sedimenting spray drift and to evaluate the potential of the different drift assessment means.

From the PDPA measurements, it was found that droplet sizes vary from a few up to some hundreds of micrometres and droplet velocities from about 0 $m.s^{-1}$ up to 16 $m.s^{-1}$. Droplet sizes and velocities are related and both are influenced by nozzle type, size and spray pressure. Droplet velocities at 0.50 m are mainly determined by the ejection velocity and by their size. Smaller droplets slow down more rapidly due to the effect of air drag compared to larger droplets. Although bigger droplet sizes generally correspond with higher droplet velocities (and vice versa) droplet velocities for one and the same droplet size range vary depending on nozzle type and size because of variations in ejection velocities. The PDPA measuring set-up was capable of producing huge amounts of useful and repeatable droplet velocity and size information under controlled conditions. Comparing the PDPA measuring results with other studies confirmed the need for reference nozzles to classify sprays because of the considerable variation of absolute results depending on measuring protocol, settings, type and variations in reference sprays and measuring equipment.

Standard flat fan nozzles produced the finest droplet size spectrum followed by low-drift and the air injection nozzles which results in significant differences in the proportion of small droplets (e.g. V_{100}, V_{200}) and different other droplet size characteristics like $D_{v0.5}$, RSF, D_{10}, etc. The effect of nozzle type on droplet sizes was more important for the smaller ISO nozzle sizes. For the same droplet size, velocities are the highest for the flat fan nozzles followed by the low-drift and the air inclusion nozzles which is caused by differences in ejection velocities resulting from the pre-orifice effect in case of a low-drift nozzle and by a combination of venturi and pre-orifice effect for the air inclusion nozzles. In spite of this, droplet velocities are generally highest for the air inclusion nozzles, followed by the low-drift and the standard flat fan nozzles - for the same ISO nozzle size and spray pressure - because of their coarser droplets corresponding with higher velocities. Hence, the droplet size effect dominates the ejection velocity effect. From the wind tunnel and field experiments, highest DRP_t and $DPRP$ values are found for the air inclusion nozzles followed by the low-drift and the standard flat fan nozzles. Again, the effect of nozzle type is most important for the smaller nozzle sizes.

The larger the ISO nozzle size, the coarser is the droplet size spectrum and the lower is the proportion of small droplets. This effect is most pronounced for the standard flat fan followed by the low-drift nozzles and is less important for the air inclusion nozzles. Bigger ISO nozzle sizes also correspond with higher droplet velocities for the same nozzle type and spray pressure. This is caused by two factors which strengthen each other namely, bigger ISO nozzles produce bigger droplets which are faster and droplets of the same size produced by bigger nozzles are faster because of higher ejection velocities. These effects of nozzle size on droplet characteristics are clearly reflected in the results from the wind tunnel and the field measurements. The bigger the ISO nozzle size, the higher the *DPRP* and DRP_t values for the standard and the low-drift flat fan nozzles. For the air inclusion nozzles, the effect of nozzle size on *DPRP* and DRP_t values is less clear but in all cases, *DPRP* and DRP_t values are high and the highest values are found for the ISO 03 nozzles.

To investigate the effect of spray pressure, a series of measurements was carried out with the ISO 03 standard flat fan nozzle within a pressure range from 2.0 to 4.0 bar. For the droplet velocities, only the fastest droplet velocity characteristics (v_{vol75} and v_{vol90}), significantly decrease with decreasing pressures. Although decreasing pressure from 3.0 to 2.0 bar did not significantly affect droplet size characteristics, fallout and airborne downwind spray deposits in the wind tunnel significantly increased because of this slight reduction in droplet velocities in combination with a decrease in entrained air velocities. On the other hand, this decrease in spray pressure resulted in a clear decrease in the amounts of field drift which was in contrast with the results from the wind tunnel and the PDPA laser measurements. Increasing the spray pressure from 3.0 to 4.0 bar significantly decreased droplet sizes but the effect was limited compared to the effect of nozzle size. In the field, an increase in spray drift was found.

Besides nozzle type, size and spray pressure, all having an effect on spray quality, driving speed and boom height also influence the amount of spray drift. Based on the field and the wind tunnel experiments, it was found that operating at a boom height as close as possible to the vegetation - without sacrificing the spray pattern - is a good way to reduce drift. The effect of driving speed could only be investigated in a realistic way in the field. A decrease in spray drift is observed for lower driving speeds of 4 and 6 $km.h^{-1}$ while the difference between the reference speed of 8 $km.h^{-1}$ and a speed of 10 $km.h^{-1}$ is statistically non-significant.

Looking at the effect of air assistance, a reducing effect on the total amount of spray drift is demonstrated for the Hardi ISO F 110 02, F 110 03 and LD 110 02 nozzles with drift reduction factors α_d of, respectively, 2.08, 1.77 and 1.53. No significant effect was found for the LD 110 03 nozzles which demonstrates that the finer the spray, the higher the impact of air assistance is on the amount of spray drift.

Comparing the results of the three drift assessment means, droplet size as well as velocity characteristics are related with field measurement DRP_t values and wind tunnel *DPRP* values. In general, DRP_t and *DPRP* values increase with increasing values of droplet diameter and velocity characteristics and decrease with increasing percentages of small droplets.

The proportion of the total volume of droplets smaller than 200 µm (V_{200}), was found to be the best individual indicator for the amount of sedimenting spray drift with an R^2 of 0.90. Besides V_{200}, the droplet size characteristics V_{50}, V_{75}, V_{100}, V_{150} and V_{250} and the velocity span factor (*VSF*) were also strongly related with DRP_t. The higher the *VSF* value, representing a less uniform droplet velocity distribution, the lower the DRP_t value which can be explained by the clear relation between droplet sizes and velocities which is reflected in the *VSF* values.
With regard to the wind tunnel measurements, the different individual droplet size characteristics are best related with $DPRP_H$ followed by $DPRP_{V2}$ and $DPRP_{V1,}$ the opposite is found for the droplet velocity characteristics. With regard to $DPRP_H$, V_{100}, V_{150}

and V_{200} have the highest predictive power ($R^2 = 0.92$), while $DPRP_{V1}$ was related most with v_{vol10} ($R^2 = 0.86$) and $DPRP_{V2}$ with *VSF* ($R^2 = 0.90$) which shows again that droplet sizes and velocities are linked and that droplet size characteristics are more related with fallout compared to airborne deposits while the opposite is found for the droplet velocity characteristics.

A fairly good correlation was found between field drift DRP_t and wind tunnel *DPRP* values with the best agreement with $DPRP_H$ ($R^2 = 0.88$) followed by $DPRP_{V2}$ ($R^2 = 0.81$) and $DPRP_{V1}$ ($R^2 = 0.66$). Moreover, similar trends are found - concerning the effect of nozzle type, size, height and pressure - from the *DPRP* and DRP_t results although there are some deviations in absolute results mainly for a varying spray pressure and nozzle height. This means on the one hand that the wind tunnel approach calculating the surface under the fallout deposit curve, is best suited to represent real near-field sedimenting drift characteristics. On the other hand it indicates that the indirect drift assessment method measuring V_{200} values is at least as well suited to represent near-field drift characteristics compared with the wind tunnel approach calculating $DPRP_H$ and even better suited compared with the wind tunnel approaches calculating $DPRP_{V1}$ and $DPRP_{V2}$. With the PDPA laser, it is only possible to investigate the effect of nozzle type, size and spray pressure whereas the effect of nozzle height can also be investigated by means of wind tunnel measurements. With both indirect techniques, it is difficult to investigate effects like driving speed and air assistance where direct drift measurements are necessary. Field research is appropriate for obtaining realistic estimates of drift under a range of working conditions but it is time-consuming and expensive. In this study, a measuring protocol and a drift prediction equation were set up to improve the interpretation of field drift data. With this equation and DRP_t of a certain spray application technique, realistic sedimenting field drift data for varying meteorological conditions can be calculated. With the indirect drift assessment means, driftability experiments can be made with different spraying systems under directly comparable and repeatable conditions and both methods are suited to permit relative studies of drift risk. Moreover, based on $DPRP_H$ or V_{200} - resulting from wind tunnel and the PDPA measurements - the DRP_t of a certain technique can be determined to come to a realistic estimate of field drift data at a driving speed of 8 $km.h^{-1}$ and a boom height of 0.50 m. This information is useful for all users of plant protection products, constructors and authorities for decision-making and risk assessment processes.

With this study, a large database with droplet characteristics, wind tunnel fallout and airborne deposits and (absolute) near-field drift results of different spray application techniques is made available together with information about the effects of climatological conditions. The results of this research are in fairly good agreement with the results from different other studies although it is difficult to compare because of differences in, among others, spray application techniques, experimental design, tracers and weather and crop conditions. That is why it is increasingly important to unify the different indirect and direct drift assessment means and to put together the different available databases.

List of abbreviations

ABBREVIATION	DESCRIPTION
AAS	Atomic absorption spectroscopy
ASAE	American Society of Agricultural Engineers (now ASABE)
BBA	Biologischen Bundesanstalt für Land- und Forstwirtschaf
BCPC	British Crop Protection Council
BSF	Brilliant sulfoflavine
C	Coarse droplet size spectrum
CDA	Controlled droplet applicator
df	Degrees of freedom
EC	Extremely coarse droplet size spectrum
EPA	Environmental Protection Agency
F	Fine droplet size spectrum & Hardi ISO 110 standard flat fan nozzles
GIS	Geographic information system
ILVO	Institute for Agricultural and Fisheries Research
Injet	Hardi ISO Injet air inclusion nozzles
ISO	International Organisation for Standardization
LD	Hardi ISO 110 low-drift nozzles
LERAP	Local Environment Risk Assessment for Pesticides (UK)
M	Medium droplet size spectrum
MS	Mean square
MSE	Mean square of error
MSR	Mean square of regression
NMD	Number median diameter
OS/*os*	Other spraying (field drift experiments/ wind tunnel experiments)
PDA	Phase-doppler anemometry
PDIA	Particle/droplet imaging analysis
PDPA	Phase doppler particle analyzer
PID	Proportional integral derivated
PMS-OAP	Particle Measuring Systems - Optical array probe
PMRA	Pest Management Regulatory Agency (Canada)
PMT	Photomultiplier tube
RS/*rs*	Reference spraying (field drift experiments/ wind tunnel experiments)
RS_v	Reference spraying used for validation
RSA	Real-time signal analyzer
rev	Revolutions
sd	Standard deviation
SDTF	Spray Drift Task Force
SE	Standard error

ABBREVIATION	DESCRIPTION
SRI	Silsoe Research Institute
SS	Sum of squares
SSE	Sum of squares of error
SSR	Sum of squares of regression
SSTO	Total sum of squares
VC	Very coarse droplet size spectrum
VF	Very fine droplet size spectrum
VMD	Volume median diameter
XC	Extra coarse droplet size spectrum

List of symbols

SYMBOL	DESCRIPTION	UNITS
A_{col}	Collection area of the spray drift collector	cm^2
A.S.	Atmospheric stability	$°C.m^{-1}$
BCPC	BCPC spray quality class based on droplet size	-
C_{spray}	Spray concentration of tracer	$g.L^{-1}$
d	Droplet diameter	m
d_e	Expanded beam waist diameter of the unfocused laser beam	m
d_i	Diameter of droplet *i*	µm
dir	Wind direction based on measurements at heights of 1.50 and 3.25 m	°
$dir_{1.50}$	Wind direction at a height of 1.50 m	°
$dir_{3.25}$	Wind direction at a height of 3.25 m	°
d_r	Roughness length	m
$drift_{dep}$	Spray drift deposit	$mL.cm^{-2}$
$drift_{OS}$	Measured drift values at a certain drift distance of one of the other sprayings	%
$drift_{RS}$	Predicted drift values of the reference spraying at a certain drift distance	%
$drift_{\%}$	Spray drift percentage	%
drift_dist	Drift distance parallel with wind direction	m
d_u	Beam waist diameter of the unfocused laser beam	m
d_w	Beam waist diameter of the focused laser beam	m
D_b	Laser beam separation	m
D_l	Line diameter	m
DIX	Drift potential index (Germany)	%
DP	Drift potential	$µL.m.L^{-1}$
DP_H	Drift potential based on numerical integration of the fallout deposit curve	$µL.m.L^{-1}$
DP_{V1}	Drift potential based on calculation of the first moment of the airborne deposit profile	$µL.m.L^{-1}$
DP_{V2}	Drift potential based on numerical integration of the airborne deposit curve	$µL.m.L^{-1}$
DP^{rs}	Drift potential of the reference spraying	$µL.m.L^{-1}$
DP^{os}	Drift potential of one of the other sprayings	$µL.m.L^{-1}$
DPRP	Drift potential reduction percentage	%
$DPRP_H$	Drift potential reduction percentage based on DP_H values	%
$DPRP_{V1}$	Drift potential reduction percentage based DP_{V1} values	%
$DPRP_{V2}$	Drift potential reduction percentage based DP_{V2} values	%
DRP	Drift reduction potential	%
DRP_t	Total drift reduction potential	%

SYMBOL	DESCRIPTION	UNITS
DRP^A	Drift reduction potential for spray application technique A	%
DRP^B	Drift reduction potential for spray application technique B	%
D_s	Stopping distance or the distance a droplet travels before its sedimentation speed is reached	m
D_{10}	Arithmetic mean diameter	µm
D_{20}	Surface mean diameter	µm
D_{30}	Volume mean diameter	µm
D_{32}	Sauter mean diameter defined as the diameter of a drop having the same volume to surface area ratio as the total volume of all the drops to the total surface area of all the drops	µm
$D_{v0.1}$, $D_{v0.25}$, $D_{v0.75}$, $D_{v0.9}$	Volume diameter below which smaller droplets constitute 10, 25, 75 and 90 % of the total spray volume	µm
$D_{v0.5}$	Volume median diameter below which smaller droplets constitute 50% of the total volume (also *VMD*)	µm
E	Beam expansion ratio	-
f	Focal length of the transmitter lens	m
f_d	Frequency of the scattered light	s^{-1}
F_{cal}	Calibration factor relating fluorimeter reading to the tracer concentration	$mg.L^{-1}$
g	Gravitational constant = 9.81 $m.s^{-2}$	$m.s^{-2}$
h_i	Height above the wind tunnel floor	m
H_i	Fallout deposit result at collector line H_i	$\mu L.L^{-1}$
l	Length of the PDPA laser measuring volume	m
n	Total number of droplets	-
N_f	Number of fringes	-
NEC	No Effect Concentration	various
NMD	Number median diameter below which the droplet diameter for 50% of the number of drops are smaller	µm
p_0	Normal atmospheric pressure = 101325 Pa	Pa
p	Pressure	Pa
p_w^s	Saturation water vapour pressure at a given temperature	Pa
PEC	Predicted Environmental Concentration	various
R^2	Coefficient of determination	-
Rc	Recovery, expressing the ratio between the measured tracer deposit and the amount of applied tracer	%
Re	Reynolds number	-
RH	(average) relative humidity (during the spray experiment) based on measurements at heights of 1.25 and 2.15 m	%
$RH_{1.25m}$	Average relative humidity at a height of 1.25 m	%
$RH_{2.15m}$	Average relative humidity at a height of 2.15 m	%
Ri	Richardson number	-
R_{blank}	Fluorimeter reading of the blanks (collector + dilution water)	-
R_{smpl}	Fluorimeter reading of the sample	-

Symbol	Description	Units
RSF	Relative span factor, a dimensionless parameter indicative of the uniformity of the drop size distribution	-
$S.R.$	Stability ratio	°C.s^2.m^{-2}
St	Stokes number	-
T	(average) temperature (during the spray experiment)	°C
T_d	Dew-point temperature	°C
$T.I.$	Turbulence intensity	-
T_x	Temperature at a height of x metres	°C
$T_{1.25m}$	Temperature at a height of 1.25 m	°C
$T_{2.15m}$	Temperature at a height of 2.15 m	°C
ΔT_{wb}	Wet bulb depression	°C
u_*	Friction velocity	m.s^{-1}
u	Wind speed	m.s^{-1}
u_z	Wind speed at a height of z metres above the ground	m.s^{-1}
v	Instantaneous wind speed at the moment of passing a sampling line based on measurements at heights of 1.50 and 3.25 m	m.s^{-1}
v_{max}	Maximum wind speed during the drift experiment	m.s^{-1}
v_{min}	Minimum wind speed during the drift experiment	m.s^{-1}
$v_{1.50m}$	Instantaneous wind speed at the moment of passing a sampling line at a height of 1.50 m	m.s^{-1}
$v_{3.25m}$	Instantaneous wind speed at the moment of passing a sampling line at a height of 3.25 m	m.s^{-1}
v_0	Droplet velocity at the nozzle exit	m.s^{-1}
v_{avg}	Arithmetic average droplet velocity	m.s^{-1}
v_d	Droplet velocity	m.s^{-1}
v_l	Liquid velocity	m.s^{-1}
v_s	Scanning speed	m.s^{-1}
$v_{s'}$	Sedimentation velocity of drops in still air	m.s^{-1}
v_{vol10}, v_{vol25}, v_{vol50}, v_{vol75}, v_{vol90}	Droplet velocity in below which slower droplets constitute 10, 25, 50, 75, 90% of the total spray volume	m.s^{-1}
V_{50}, V_{75}, V_{100}, V_{150}, V_{200}, V_{250}	Proportion of total volume of droplets smaller than 50, 75, 100, 150, 200 and 250 µm in diameter	%
V	Average wind speed during the spray experiment based on measurements at heights of 1.50 and 3.25 m	m.s^{-1}
$V_{1.50m}$	Average wind speed during the spray experiment at a height of 1.50 m	m.s^{-1}
$V_{3.25m}$	Average wind speed during the spray experiment at a height of 3.25 m	m.s^{-1}
V_{app}	Spray volume	L.ha^{-1}
V_{dil}	Volume of dilution liquid	L
V_i	Airborne deposit result at collector line V_i	µL.L^{-1}
VMD	Volume median diameter below which smaller droplets constitute 50% of the total volume (also $D_{v0.5}$)	µm

SYMBOL	DESCRIPTION	UNITS
VSF	Velocity span factor, a dimensionless parameter indicative of the uniformity of the drop size velocity distribution	-
w	Width of the probe volume	m
x	Length of the rectangular scan pattern	m
Δx	Distance intervals in the X direction during scanning	m
Δx_i	Distance interval corresponding with collector line H_i	m
X	First order linear regression independent variable	various
X_{H_2O}	Absolute humidity of the air expressed in grams of water vapour per unit mass of dry air	$g.kg^{-1}$
y	Width of the rectangular scan pattern	m
Δy	Distance intervals in the Y direction during scanning	m
z	Height above the ground	m

GREEK SYMBOLS	DESCRIPTION	UNITS
α	Signifance level	-
α_d	Drift reduction factor expressing the ratio between the amount of spray drift of two different spray application techniques	-
κ	von Karman’s constant = 0.41	-
υ_a	Kinematic viscosity of air	$m^2.s^{-1}$
υ_L	Kinematic viscosity of the liquid	$m^2.s^{-1}$
τ	Surface shearing stress	$N.m^{-2}$
ρ_a	Density of the air	$kg.m^{-3}$
ρ_d	Density of the droplet	$kg.m^{-3}$
Γ	Dry adiabatic lapse rate ≈ -1 °C/100 m	$°C.m^{-1}$
θ	Angle between laser beams	°
θ_t	Potential temperature	K
γ	Heat capacity ratio of the air	-
Ø	Diameter	m
λ	Laser light wavelength	m
δ	Deviation of the ideal driving direction on wind direction	°
δ_f	PDPA laser fringe spacing	m

Table of contents

Chapter 1 **General introduction**

1.1. Introduction

Society's preoccupation with chemical use in agricultural processes has increased significantly during the last few years. In particular, the relation between both health and environmental issues with pesticide dose is a persistent problem in rural and urban areas. The sustainable food production will depend, in the foreseeable future, on the continued use of energy and chemical inputs. The effectiveness of all chemical pesticide and fertiliser products depends on the user's ability to place the correct quantity of chemical on the intended target with the minimum loss to the environment. When pesticides are applied to crops some of the spray may move beyond the intended area as spray drift.

Spray drift and risks connected with application of pesticides in agriculture are attracting increased attention from the general public as well as the scientific community and drift of pesticides caused by spraying has been recognised as a major problem for the environment. That is why, drift-reducing application technology is a vital and important part of our crop production systems.

For a good understanding, it is important that there is no doubt about what is meant by the term 'spray drift' in this work. Therefore, in the general introduction the definition and importance of spray drift is described in section 1.2 followed by the mechanisms of drift formation (§ 1.3) and the magnitude of spray drift from ground sprayers (§ 1.4). The objectives and outline of this thesis are explained in section 1.5.

1.2. Definition and importance of spray drift

1.2.1. Definition of spray drift

Pesticides are most usually applied as a spray of liquid droplets. In general, spray drift is defined as that portion of the applied product (representing pesticide active ingredient) which is moved out of the target area by the action of climatic conditions during and as a consequence of the application process.
Himel (1974) considered spray lost from the target area by the action of wind on droplets as 'exo-drift' whereas spray that was lost to the soil rather than being retained on plant or insect targets was termed 'endo-drift'. Endo-drift arises mainly from bounce and run-off of large droplets and high spray volume rates. However, this work is concerned with the losses from the intended spray treatment zone by the action of wind. There are two important mechanisms in which pesticides move downwind, namely vapour drift and particle drift (Figure 1.1).

Vapour drift occurs when pesticide molecules evaporate into the air from sprayed surfaces within the treatment zone such that they can later be moved downwind as vapour. This kind of drift is mainly related to the chemical's properties and/or formulation (such as vapour pressure and Henry's constant) and less to the type of application used. Since the chemical is moving as a gas rather than in liquid droplets, it must be assessed and managed according to different methods and was studied among others by Carlsen *et al*. (2006 a). Vapour drift can occur more than 12 hours after application, especially when temperatures are high (Matthews, 2006).

Particle drift is the movement of spray particles or droplets, formed and moved from the intended treatment zone during application. This work focuses on particle drift which, for the purposes of this thesis, is called spray drift from now on. Spray drift, as described in this thesis, is therefore defined as follows:

> "Spray drift is the physical movement of droplets through the air at the time of the application or soon thereafter from the intended treatment zone to any non-target site. Spray drift does not include movement of agricultural chemicals to non-target sites caused by volatilization, erosion, surface or groundwater transport or windblown soil particles that occurs after application".

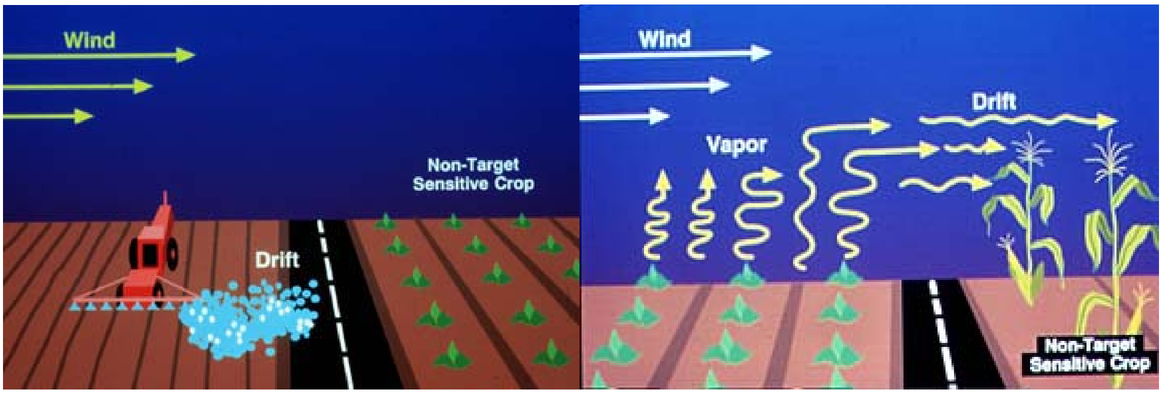

Figure 1.1: Visualisation of droplet drift (left) (Woody, 2002) and vapour drift (right) (Ohioline, 2002)

Many factors may interact to cause or influence the magnitude of drift: equipment design and application parameters, spray physical properties and formulation and meteorological conditions are all recognised (Salyani & Cromwell, 1992).

In the past, contrasting definitions of spray drift were used by different researchers (Bache *et al*., 1988). Examples of how results of spray drift experiments have been expressed are:

- Comparative values of drift from different spraying equipment using the units appropriate to the collection system employed (Ford, 1984; 1986; Longley *et al.*, 1997; Taylor *et al.*, 2004). As described in section 4.2.4, a comparable approach was followed to express downwind spray deposits from the wind tunnel experiments.
- The percentage of sprayer output that is airborne at a defined distance downwind of the directly sprayed zone (Miller, 1993).
- The percentage of sprayer output calculated by integration of sedimenting drift up to a defined distance from the field boundary plus the integrated airborne drift at the defined distance (Eichhorn, 1990).
- The percentage of the intended applied dose or the percentage of sprayer output that is moved to a defined distance from the field boundary (Salyani & Cromwell, 1992; van de Zande, 2000 a & b). This approach was followed to calculate drift depositions from the field measurements as described in section 5.2.3.

The ISO 22866 (2005) 'Equipment for crop protection - Methods for the field measurement of spray drift' offers a well-developed, accurate, appropriate and most of all a standardised method for measurement of spray drift that will permit a more rational approach to the assessment of, for example, controlling measures. This standard is described in section 2.3.4.1.

1.2.2. Importance and consequences of spray drift

Advances in research on new molecules and chemical agents, as well as in agricultural engineering, have allowed to reduce the amounts of pesticide for crop protection. Nevertheless, according to Candela (2003), pesticide use in Europe amounts up to about 500×10^6 kg.year^{-1} with an average dose of 4.3 kg.ha^{-1}.

During application, 30 up to 50% of the amount applied can be lost to the air (Van den Berg *et al*., 1999). Pesticide application to crops and soils for agricultural purposes is a major source of persistent organic pollutants in the atmosphere.

Spray drift can cause crop protection chemicals to be deposited in undesirable areas with serious consequences, such as (Ozkan *et al*., 1993; Nuyttens *et al.*, 2004 c):

- Damage to sensitive adjoining crops, plants and other susceptible off-target areas. This assessment considers the toxicity of the chemical to plant species and has been studied and demonstrated for natural communities by Nordby and Skuterud (1974), Marrs *et al*. (1989; 1993), Kleijn and Snoeijing (1997), Marrs and Frost (1997) and de Snoo and van der Poll (1999). Damage from herbicides to adjoining crops has been studied among others for rapes (Arvidsson, 1985), wheat (Yates *et al*., 1978), beans (Byass & Lake, 1977) and tomatoes (Greek, 1984).
- Environmental contamination such as water contamination and illegal pesticide residues. Particular attention is given to wetlands, surface streams and rivers.
- Health risks for animals and humans. For health risks, the assessment considers the toxicity of the chemical and the likelihood that harmful quantities of spray drift would contact people or animals either directly or indirectly such as through contact with plants or structures affected by spray drift. Effects of spray drift have been studied on non-invertebrates (Davis & Williams, 1990; Longley & Sotherton, 1997; de Snoo & van der Poll, 1999) as well as on vertebrates like birds (Rands, 1985; de Snoo, 1999), different types of mammals (Kleijn & Snoeijing, 1997) and humans (Lloyd *et al*., 1987; Gilbert & Bell, 1988).
- A lower dose than intended on the target field and an uneven spray distribution which can reduce the effectiveness of the pesticide, wasting pesticide and money.
- Over-dosing if the farmer knowingly over-applies chemicals to compensate for drift losses and to ensure the desired level of control.

Hence, it is clear that the amount of drift which can be tolerated depends on many factors.

1.3. Mechanisms of drift formation

1.3.1. Droplet generation

The process of generating drops is called atomization. In order to create a droplet, which carries and transports the active ingredient to the target, energy must be expended on the bulk spray solution. This can be done by different methods (PISC, 2002):

1. *Pressure* – by forcing the spray liquid under pressure through a small orifice. It causes the liquid to emerge as small ligaments which break up further into droplets. Such devices are normally referred to as hydraulic nozzles and they are available in a number of different types designed for different purposes. The most common types of hydraulic nozzles are flat fan nozzles, cone nozzles and deflector nozzles (§ 2.2.1.3). This kind of droplet generation is by far the most popular in European agriculture (Figure 1.2).

2. *Centrifugal* – by subjecting the liquid to centrifugal energy. By precisely feeding liquid onto a spinning disc, it is possible to generate droplets at the edge of the disc as liquid is spun off into the surrounding air. Droplet size is influenced by the rotational speed of the disc, the design of the disc and the liquid flow rate. Such spinning discs are normally referred to as controlled droplet applicators (CDA) as they generally produce a narrower range of droplet sizes than hydraulic nozzles (Figure 1.2). This type of nozzles is also called rotary nozzle and low application rates are normally used.

3. *Air shear* – by subjecting liquid to high velocity air, droplets can be generated as the liquid is torn into small particles by the mechanical impact of the moving air stream. By adjusting the air speed and liquid flow rate, droplet size can be altered. With air shear nozzles, the energy exerted by the air is used to produce the droplets.

4. *Vibration* – by utilising vibrational energy. This type of nozzles includes ultrasonic nozzles, vibrating tips, piezoelectric crystal devices, etc. They are primarily for experimental purposes and are not available for commercial spraying.

5. *Electrostatic* – by using electrical charge. A few electrostatic nozzles are available commercially but are not widely used. Theory suggests that charged small droplets can be attracted to a plant surface and this can lead to a reduction of spray drift.

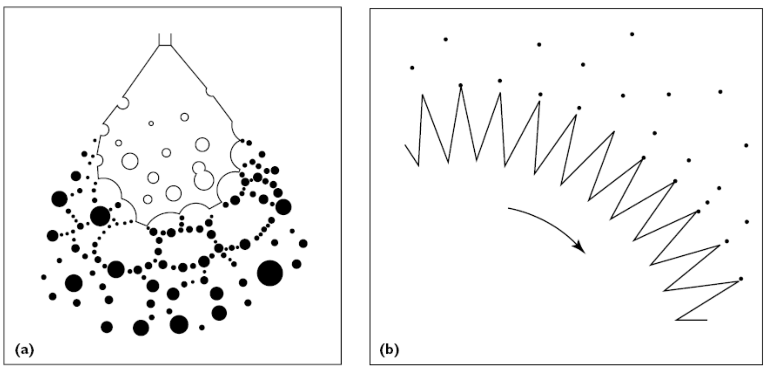

Figure 1.2: Droplet formation from (a) hydraulic nozzle and (b) spinning disc

1.3.2. Drift formation

Detailed mechanisms by which droplets become detrained from sprays generated on a moving vehicle are often complex. With a conventional boom sprayer, spray from nozzles is directed downwards onto the target area. The spray leaves the nozzle as a continuous liquid sheet travelling at a velocity normally in the range of 15-25 m.s^{-1} and then breaks up into droplets (Dombrowski & Johns, 1963). Interaction of the spray with the airflow around it arising from the induced downward air current from the nozzle, natural wind conditions and the forward motion of the vehicle, creates vortex conditions at the edge of the spray fan, which leads to the detrainment of small droplets. In case of boom sprayers, droplets are released in close proximity to the canopy target, thus initial energy exerted by the nozzle influences the transport of droplets over short ranges.

Close to the position of spray formation, all droplets have a high downward velocity but after ejection from the atomizer, the particle motion is decelerated as a result of air resistance (drag). The effect of air drag is such that the smaller droplet sizes slow down rapidly to the speed of the entrained air. According to Jörgensen (2003) the induced downward air current from the nozzle creates a depression around the nozzle and as the nozzle is moved forward in the air, this depression is filled by air coming from the front. There still has to be a compensation for the depression behind the nozzle. Air moves up from behind the nozzle to maintain pressure equilibrium and a vortex is created behind the nozzle (Figure 1.3). Depending on their momentum, the droplets are deflected more or less from their 'vertical' trajectory. This is confirmed by Courshee (1959), Miller *et al.* (1989 a) and Young (1990; 1991) whose experimental results showed that the largest downwind displacement of spray volume occurred at the edges of the spray sheet. The interaction between the spray cloud and airflows associated with the natural wind and the forward motion of the sprayer becomes more important as a result of the trend to operate at higher speeds with lower spray volume rates in order to increase work rates.

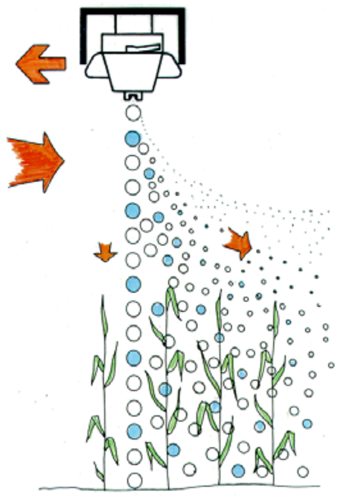

Figure 1.3 Aerodynamics of a flat fan spray nozzle moving in still air (Jörgensen, 2003)

The characteristic time in which the droplet adjusts itself to the sedimentation velocity ($v_{s'}$) is termed relaxation time. This relaxation time is the time in which a particle adjusts itself to an applied force. During the relaxation time, the particle travels a distance known as the stopping distance (D_s), a distance of travel associated with the inertia of the particle. The effects of inertia become significant in situations where the particle motion is non-uniform for example deceleration following ejection from a spray nozzle. The stopping distance D_s (m) can be expressed by the following formula (Bache & Johnstone, 1992):

$$D_s = \frac{v_0 . d^2 . \rho_d}{18. \upsilon_a . \rho_a} \qquad (1.1)$$

Where

v_0 = Droplet velocity at the nozzle exit (m.s^{-1}),
d = Droplet diameter (m),
ρ_d = Density of the droplet (kg.m^{-3}),
ρ_a = Density of the air (kg.m^{-3}),
υ_a = Kinematic viscosity of air (m².s^{-1}).

The relevance of the stopping distance can be seen in the case of hydraulic nozzles on a boom 0.5 m above the crop. Droplets larger than 200 µm are likely to be projected directly into the crop, while those smaller than 50 µm acquire the local air velocity soon after leaving the nozzle. Intermediate size drops reach part of the distance to the crop before being significantly affected by wind and turbulence.
The sedimentation speed $v_{s'}$ (m.s^{-1}) for drops smaller than 50 µm can be expressed as (Bache & Johnstone, 1992):

$$v_{s'} = \frac{g.d^2.(\rho_d - \rho_a)}{18. \upsilon_a . \rho_a} \qquad (1.2)$$

Where g is the gravitational constant (9.81 m.s^{-2}). For droplets up to 100 µm a rough estimation of the sedimentation speed may be done with the following simplified formula (Elliott & Wilson, 1983):

$$v_{s'} = 3 \times 10^7 . d^2 \qquad (1.3)$$

Within the surface layer, the variation in wind speed is dominated by the frictional drag exerted on the flow by the underlying surface. The force exerted by the wind on the surface is called the surface shearing stress τ. This shearing stress is proportional to the square of the friction velocity u_*:

$$u_*^2 = \frac{\tau}{\rho_a} \qquad (1.4)$$

where

u_* = Friction velocity (m.s^{-1}),
τ = Shearing stress (N.m^{-2}).

The friction velocity u_* can be calculated using the logarithmic wind law (Bauer *et al*., 2004):

$$u_z = \frac{u_*}{\kappa} . \ln\left(\frac{z + d_r}{d_r}\right) \qquad (1.5)$$

where

u_z = Wind speed at a height z above the ground (m.s^{-1}),
κ = von Karman's constant = 0.41,
z = Height above the ground (m),
d_r = Roughness length (m).

Sedimentation dominates the movement of the droplets in the wind profile if $\frac{v_{s'}}{u_*} \geq 3$, but on the other hand turbulence dominates the movement of the droplet if $\frac{v_{s'}}{u_*} \leq 0.3$ (Elliot & Wilson, 1983). In the region between these extremes, a combination of sedimentation and turbulent movement will mean that droplet trajectories are prone to deflection by the wind and, coupled with the evaporation of water-based sprays, may give substantial volumes of spray drift (Lawson, 1979).

A simple model, known as Porton model (PISC, 2002), can be used to predict downwind distances travelled by droplets as long as the effects of turbulence and evaporation are ignored. Table 1.1 illustrates the *theoretical* downwind distance droplets would be transported if released 3 metres above a crop in a steady crosswind of 1 m.s^{-1}. In practice, effects such as turbulence and droplet evaporation have a major influence on downwind deposition and need to be taken into account.

Table 1.1: Porton model predicted distances for downwind transport for a release height of 3 m (PISC, 2002)

Droplet diameter (µm)	Terminal velocity (m.s^{-1})	Time to fall 3 m	Downwind displacement in 1 m.s^{-1} wind (m)
10	0.003	16.9 min	1000
20	0.012	4.2 min	250
50	0.075	40.5 s	40
100	0.28	10.9 s	10.7
500	2.14	1.7 s	1.4
1000	5.0	0.8 s	0.6

1.4. The magnitude of spray drift from ground sprayers

German spray drift data were gathered by different research institutes and agrochemical manufacturers for different spray application techniques (spray pressure, nozzle type, etc.) and climatological conditions (Ganzelmeier & Rautmann, 2000). Based on 50 drift trials for field sprayers, Rautmann *et al*. (2001) found that drift in field crops can be expressed as:

$$y = 2.7705.x^{-0.9787} \qquad (1.6)$$

where y is the amount of sedimenting spray drift in % of the application rate and x is the distance in metres from the treated area. This equation was also tested by Carlsen *et al*. (2006 b) and was found to correspond reasonably well with their drift measurements. With this equation however, the information on changes in drift with various factors like meteorology, application and formulation is lost. Moreover, 19 out of 50 experiments were based on measurements with low-drift nozzles and the 90% percentiles of the drift values were used. That is why results of other researches reflect higher spray depositions when all measurements were performed with a medium spray quality nozzle (van de Zande *et al*., 2002 a; Carlsen *et al*., 2006 b).

Hewitt and Wolf (2004) made some initial efforts to set-up an international database on pesticide drift including data from the UK, Germany, The Netherlands and the US. In Figure 1.4, an overview is presented of drift data from different sources (Ganzelmeier *et al*., 1995; Arvidsson, 1997; SDTF, 1997; BBA, 2000 b; Gilbert, 2000; van de Zande *et al*., 2002 a). In this figure, drift deposition is calculated as a percentage of the deposition on the sprayed area. It shows that curves can differ by as much as a factor of ten. Differences in the absolute levels of drift can be attributed to different factors like weather conditions and spray application technology, as described in detail in this thesis.

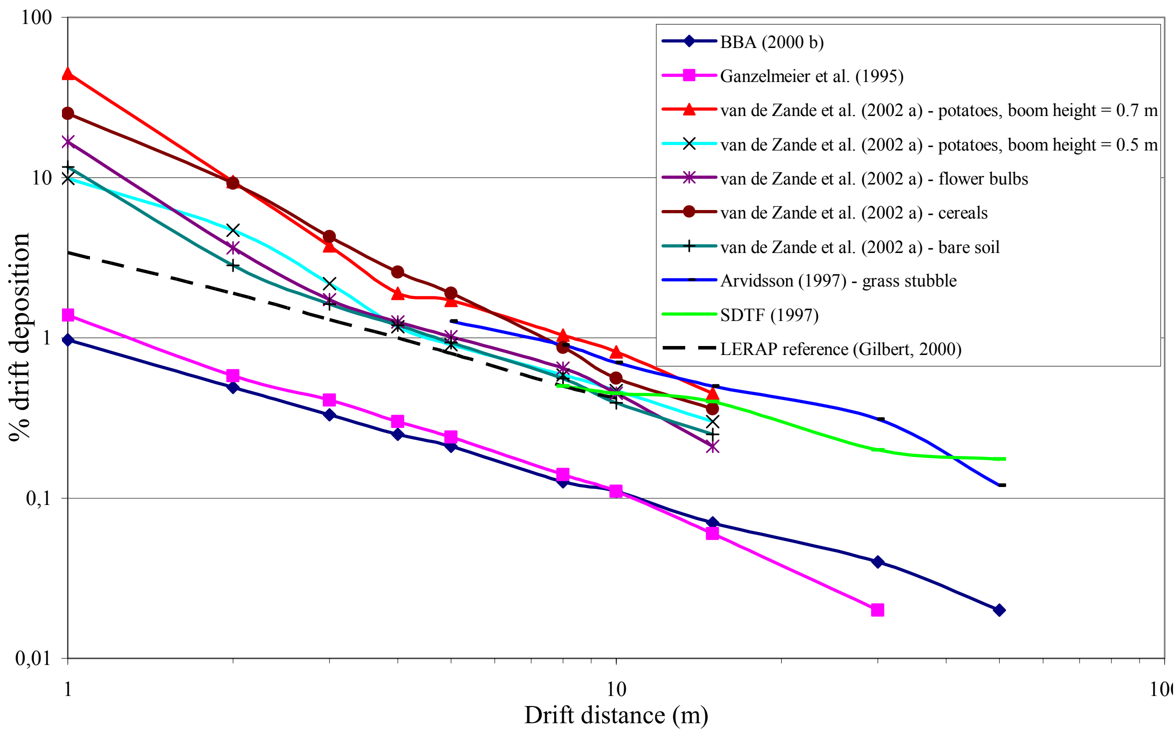

Figure 1.4: Data from various sources on the effect of crop type on spray drift (adapted from: van de Zande, 2002; Focus, 2005)

1.5. Objectives and outlines of this work

From the previous sections, it can be concluded that drift of pesticides caused by spraying may cause a major problem for the environment and can possibly be reduced by the selection of an appropriate spray application technique.

Therefore, the general objective of this doctoral research is **to investigate the influence of spray application technology on the amount of spray drift from field crop sprayers using indirect and direct drift assessment means** namely PDPA laser, wind tunnel and field drift measurements.

To achieve this main objective, the following sub-objectives will be addressed, each corresponding with one of the following chapters:

- To describe the state-of-the art of drift reduction techniques including the different factors related to spray drift, the different types of experiments, the available spray drift models and the international drift regulations (Chapter 2),

- To measure and compare droplet size and velocity characteristics of different nozzle-pressure combinations using a Phase Doppler Particle Analyzer (PDPA) laser measuring set-up and protocol (Chapter 3),

- To measure airborne and fallout wind tunnel spray deposits of different spray application techniques, to calculate their drift potential using contrasting approaches and to compare these drift potential results with the reference spraying by calculating their drift potential reduction percentage (*DPRP)* (Chapter 4),

- To investigate the effect of spray application technology and meteorological conditions on the amount of sedimenting spray drift under field conditions and to compare these results with the reference spraying by calculating their drift reduction potential (*DRP)* (Chapter 5),

- To compare the results obtained with the indirect drift assessment means, i.e. PDPA laser and wind tunnel, with the results from the field drift measurements and to evaluate the potential of these three different drift assessment means (Chapter 6).

Finally, the general conclusions of this thesis and some guidelines for future research are given in Chapter 7. In Figure 1.5, a schematic overview of the outline of this thesis is presented.

1.6. Selection of spray application techniques

The different investigated spray application techniques were selected based on common Belgian and international agricultural practice. The **reference spraying** was defined as a standard horizontal spray boom without air assistance with a spray boom height and nozzle distance of 0.50 m, ISO 03 standard flat fan nozzles at a pressure of 3.0 bar and a driving speed of 8 $km.h^{-1}$ (resulting in an application rate of approximately 180 $L.ha^{-1}$).

Besides this reference spraying, different other spray application techniques were tested to evaluate the effect of:

- Nozzle type (standard flat fan, low-drift, air inclusion),
- Nozzle size (ISO 02, 03, 04 and 06),
- Spray pressure (2.0, 3.0 and 4.0 bar),
- Driving speed (4, 6, 8 and 10 $km.h^{-1}$),
- Spray boom height (0.30, 0.50 and 0.75 m),
- Air assistance.

The reference spraying is used for a comparative assessment of the different other spray application techniques whereas measurements with the different spray application techniques were performed with the PDPA laser, in the wind tunnel and in the field.

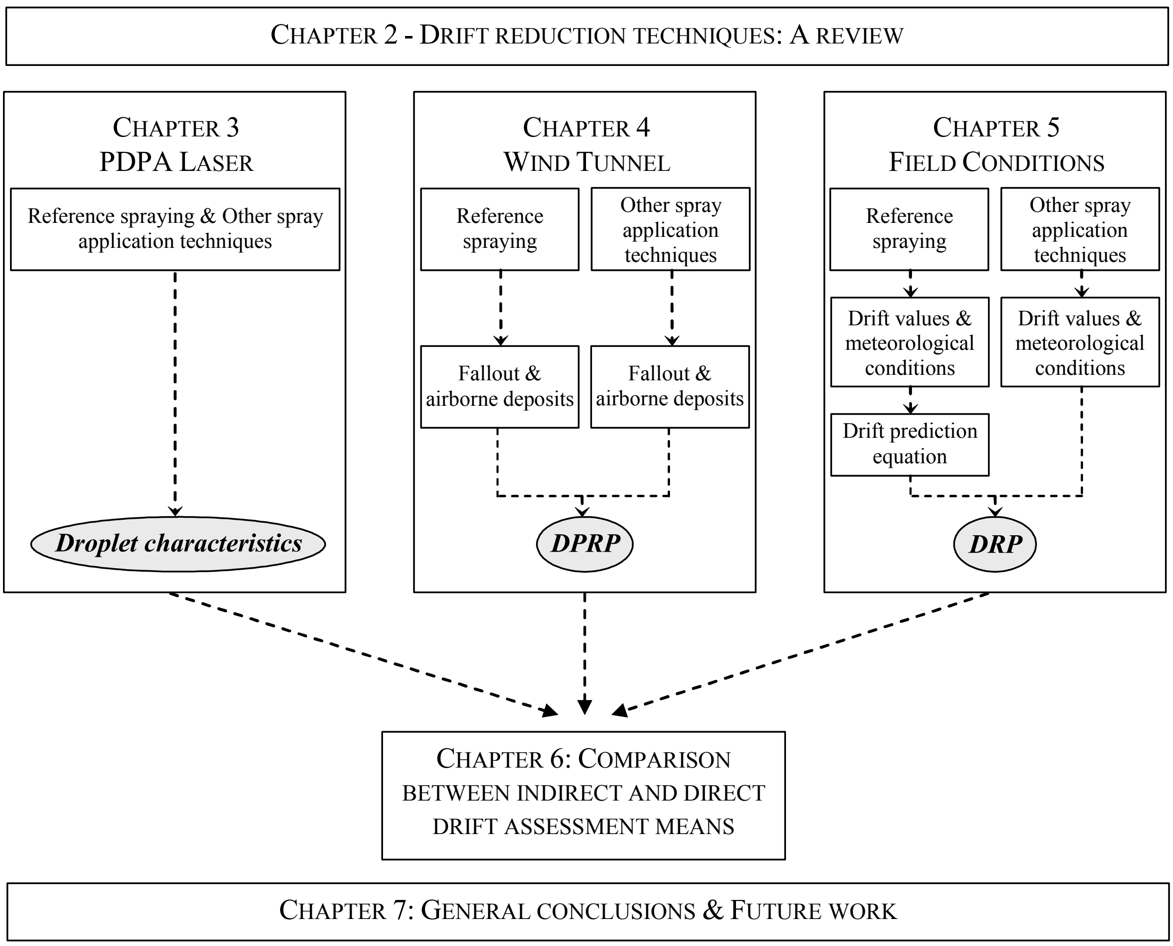

Figure 1.5: Schematic representation of the outline of this thesis

Chapter 2 ***Drift, drift mitigation strategies and its measurement: A review***

2.1. Introduction

When pesticides are applied to crops some of the spray may move beyond the intended area. Drift from pesticides during spray application is related to a wide range of factors, as described in section 2.2, like spray quality (§ 2.2.1), different sprayer factors (§ 2.2.2), spray liquid properties (§ 2.2.3), climatic conditions (§ 2.2.4), drift collectors and windbreaks (§ 2.2.5), crop characteristics (§ 2.2.6) and the presence of buffer zones (§ 2.2.7) (Nuyttens *et al.*, 2004 c).
Different approaches for spray drift research have been suggested like spray quality experiments (§ 2.3.2), wind tunnel experiments (§ 2.3.3) and field experiments (§ 2.3.4) using different spray drift sampling and tracing techniques (§ 2.3.1). Besides the experimental research, a lot of spray drift modelling activities have already been carried out (§ 2.4). Finally, in section 2.5 an overview is given of the most important international drift regulations.

2.2. Factors related to spray drift

There are a large number of factors influencing the risk of spray drift during application of plant protection products. New and improved solutions to reduce this problem are also continuously under development. All these factors may be classified in the following groups (Nuyttens *et al*., 2004 c):

- Spray quality
- Sprayer factors
- Spray liquid properties
- Climatic conditions
- Drift collectors and windbreaks
- Buffer zones or no-spray zones
- Operator care, attitude and skill

Besides these possible technical solutions, it is clear that the competence of the people who apply chemicals is the foundation of all risk mitigation approaches. That competence implies an understanding of all important risk factors affecting spray drift and demands a responsible and constructive attitude on the part of the operator.

2.2.1. Spray quality

Pressure nozzles produce sprays with a range of droplet sizes and velocities (Lefebvre, 1989). It is important to note that different designs of nozzles have a wide range of features in relation to droplet size and velocity distribution and drift reduction that can be achieved. Hence, it is important to quantify and control the droplet characteristics because they influence droplet trajectories and interaction with the target. The ideal spectrum will maximize spray efficiency for depositing and transferring a biologically effective dose to the target, while minimizing off-target losses. Insecticides and fungicides generally require smaller droplets than herbicide applications to obtain adequate coverage of the target (Hewitt, 1997). The relation between spray quality and biological efficacy is described in section 2.2.1.5.

The movement of droplets has components relating to both the velocity and the direction of travel. With most nozzle designs, increasing the spray pressure increases the velocity of droplets but also results in a finer spray (Barnett & Matthews, 1992; Etheridge *et al.*, 1999). The balance between these two factors varies mainly upon nozzle design and pressure level. Droplet directions can be changed by varying the spray fan angle from flat fan nozzles (Miller, 1999). Large droplets maintain a downward velocity longer than smaller ones and small droplets also evaporate faster. Miller *et al.* (1995 b) concluded that spray drift is not only related to droplet size but also to droplet velocity and direction.

2.2.1.1. Droplet size

Within the spray equipment system, droplet size is one of the most influential factors related to drift (Courshee, 1959; Satow *et al.*, 1993; Bird *et al.*, 1996; Carlsen *et al.*, 2006 b). The droplet size distribution depends on nozzle type, nozzle size, liquid properties and spray pressure and is of importance for crop coverage and the biological efficacy of the applied pesticide (Klein & Johnson, 2002). When the pressure is increased, most nozzles generate a finer droplet size spectrum (Mueller & Womac, 1997; Ozkan, 1998; Etheridge *et al.*, 1999). Droplet size, speed and direction influence driftability. Larger droplets retain their momentum for longer and are therefore less prone to crosswinds which can cause drift. Although there is no specific droplet size range that is liable to drift under all conditions, many researchers have considered droplets smaller than 75 µm (Miller & Hadfield, 1989; Hobson *et al.*, 1990; 1993), 100 µm (Byass & Lake, 1977; Grover *et al.*, 1978; Bode, 1984), 150 µm (Yates *et al.*, 1985; Combellack *et al.*, 1996) or 200 µm (Bouse *et al.*, 1990) to be the most drift prone. However, Butler Ellis and Bradley (2002) concluded that there is a poor correlation between spray volume contained in droplets smaller than 100 µm and drift. In this work, the relation between droplet characteristics and drift potential is discussed in section 6.2.2.

Since the optimum droplet size for efficacy and collection on target surfaces is often considerably smaller (§ 2.2.1.5), a compromise must often be reached in the spraying operation. A study carried out by Zhu *et al.* (1994) using a computational fluid dynamics computer model (§ 2.4.2) indicated that spray particles under 50 µm in diameter remain suspended in the air indefinitely or until they evaporate. The viscosity of spray mixtures can greatly influence the sizes of spray droplets (Reichard *et al.*, 1996) (§ 2.2.3.3).

No practical nozzle system used in agriculture produces droplets that are all the same size. All commercial nozzles generate a range of droplet sizes. A summary of the main values that are used to describe these spectra is presented in Table 2.1.

Table 2.1: Overview of some parameters to describe droplet size spectra

Parameter	Description	Units
VMD or $D_{v0.5}$	Volume median diameter or diameter for which a volume fraction of 50 percent is made up of drops with diameters smaller than this value	µm
$D_{v0.1}$, $D_{v0.9}$	Diameter at which a volume fraction of 10, 90 percent is made up of drops with diameters smaller than this value	µm
RSF	Relative span factor; dimensionless parameter indicating the uniformity of the drop size distribution $= \frac{D_{v0.9} - D_{v0.1}}{VMD}$	-
NMD	Number median diameter; droplet diameter for which 50% of the number of drops is smaller than this value	µm
$\frac{VMD}{NMD}$	Measure of the width of the droplet size distribution	-

The volume median diameter (*VMD*) is the most commonly used descriptor of droplet size of a spray fan. One half of the total volume of droplets is made up of droplets smaller than the *VMD* and the other half of droplets larger than the *VMD*. Two nozzle-pressure combinations with the same *VMD* may actually produce a quite different droplet spectrum. One nozzle may produce droplets that fall in a very narrow band around the *VMD*, while the other nozzle may produce a very large range of droplet sizes. Droplet spectra are normally represented by a frequency histogram or an accumulated volume curve.
Moreover, the size distribution of droplets in agricultural sprays is not homogeneous and depends on the position within the spray (Butler Ellis *et al*., 1997; Lund & Matzen, 1996; Chapple & Hall, 1993).

2.2.1.2. Droplet velocity and trajectory

The movement of droplets leaving a nozzle has components relating to both the velocity and direction of travel. Increasing the spray liquid pressure with most nozzle designs not only results in a finer spray but also increases the velocity of droplets leaving the region of spray formation. As the effect of making a finer spray dominates with initial increases of pressure, the risk of drift tends to increase. Further increase in pressure does not result in a further increase of drift and may even, with some nozzle designs, result in a decrease in drift at a high pressure due to the dominance of the droplet velocity effect (Miller & Smith, 1997). In general, increasing the initial downward droplet velocity decreases drift distances (Ozkan, 1998).

The speed at which a droplet falls when released into (still) air - the sedimentation velocity - is strongly related to its diameter. A 250 µm droplet has a sedimentation velocity of approximately 1 $m.s^{-1}$ and so will fall to the ground very shortly after its release. A 100 µm however, has a sedimentation velocity of 0.25 $m.s^{-1}$ and is more subject to drift (formula 1.3). Finally, a 10 µm droplet has a sedimentation velocity of only 0.003 $m.s^{-1}$ (formula 1.2). Adequate control of droplet size is therefore essential if spray drift needs to be managed effectively.

Sidahmed (1996) formulated a drop-size/velocity equation based on the energy balance equation and evaluated this equation with effective measuring data (Sidahmed *et al*., 1999) and concluded that a droplet velocity at formation is dependent on its diameter.

Variation in the spray angle from flat fan nozzles is one way in which droplet directions (trajectories) can be changed. Hobson *et al*. (1993) used a computer model to relate data describing the droplet size distribution and trajectory angles for conventional flat fan with 80° and 110° fan angle to drift and concluded that, if the nozzle height was adjusted appropriately, then the drift for the 110° fan angle was less than for the 80° case. This result indicates that the effect of nozzle height is likely to dominate over the combined effects of the reduced droplet size and wider trajectory angles with the 110° nozzles. This emphasises the importance of maintaining the nozzle at the correct working height which is described in detail in section 2.2.2.1.

2.2.1.3. Nozzle types

The two most important nozzle types are flat fan nozzles and cone nozzles.

A. Flat fan nozzles

Flat fan nozzles have always been preferred on horizontal boom sprayers, where the nozzles are mounted on a horizontal boom. Nowadays, flat fan nozzles are almost exclusively used on field sprayers. With these nozzles, a very good cross distribution can be achieved under a spray boom with the correct nozzle spacing and spray height. Flat fan nozzles produce a fan-shaped spray pattern. There are different types of flat fan nozzles: standard flat fan nozzles, drift-reducing or pre-orifice flat fan nozzles and air inclusion flat fan nozzles. The choice of nozzle type will often be a compromise between optimal biological effect and consideration for drift, capacity, speed, etc.

Standard flat fan nozzles

Standard flat fan nozzles have the smallest droplets compared to drift-reducing and air inclusion nozzles for the same nozzle size and spray pressure. The small droplets secure an unsurpassed liquid distribution and a very effective coverage of the surface of the spray target. Unfortunately, small droplets are very drift prone.

Drift-reducing flat fan nozzles

Drift-reducing flat fan nozzles or pre-orifice nozzles can achieve a coarser droplet size range at equal pressures without a reduction in flow rate by the creation of a thicker spray sheet. This has been accomplished by adding a pre-orifice to the nozzle tip assembly just ahead of the conventional discharge orifice (Figure 2.1). The function of this pre-orifice plate is to decrease the liquid pressure and velocity in the chamber of the flat fan nozzle. The lower pressure together with a larger orifice results in a thicker spray sheet and a coarser spray (Jensen, 1999; Miller, 1999). Therefore, the drift-reducing nozzles are less drift prone. Ozkan *et al*. (1997) and Wolf and Frohberg (2002) showed that significant drift reductions could be obtained by using drift-reducing flat fan nozzles. Barnett and Matthews (1992) found that drift-reducing flat fan nozzles reduce the volume of spray emitted in drift susceptible droplets < 100 µm at lower flow rates. In addition, the volume of droplets > 300 µm also increased.

Miller (1999) stated that droplets from pre-orifice nozzles travel more slowly than from standard flat fan nozzles operating at the same pressure and flow rate. This means that the level of drift reduction achieved by the pre-orifice design is less than would have been predicted only by considering the percentage of spray volume in small droplet sizes.

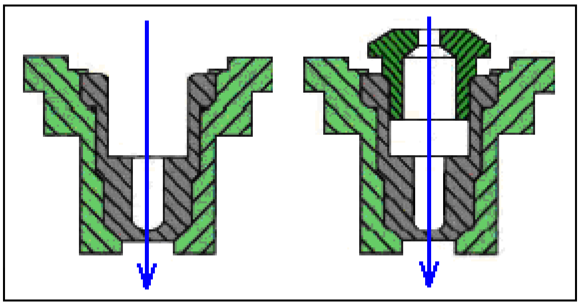

Figure 2.1: Standard flat fan and drift-reducing flat fan nozzle

Air inclusion flat fan nozzles

Air inclusion flat fan nozzles (also air injection or venture flat fan nozzles) contain a venturi insert. This venturi induces air through two holes at the side of the nozzle (Figure 2.2). The air is mixed with the liquid in the nozzle chamber. Because the liquid leaving the flat fan orifice is a mixture of air and spray liquid, the sheet very quickly gets unstable and breaks up into droplets. The bubbles of entrained air perforate the sheet before it would normally have disintegrated. This results in a very coarse spray. In some cases the droplets can contain air inclusions and the amount of small droplets is less than for standard flat fan nozzles. This is confirmed by different researchers like Etheridge *et al*. (1999) and Derksen *et al*. (1999). Moreover, the amount of air inclusions in the droplets and their size are very dependent on the chemical and the additives (surfactants, oils, stickers etc.) used. If the air-volume ratio is above 10% it may, for some chemical products, compensate for less target surface coverage that has been caused as a consequence of fewer available droplets; both surface impact and spreading characteristics of these drops may be different from those conventionally produced. Faggion *et al*. (2006) developed a technique for assessing the quantity of included air in droplets. The coarse atomization results in a considerably reduced number of small droplets. In general, this leads to a clear drift reduction as demonstrated by Derksen *et al*. (1999) and Klein and Johnson (2002). Wolf and Frohberg (2002) found that air injection nozzles and drift-reducing flat fan nozzles produced similar drift results while Piggott and Matthews (1999) stated that there is a wide variation in spray quality due to the design of the Venturi system.
According to Miller (1999), for this type of nozzles an increase of spray pressure initially increases and then reduces drift due to the dominance of the droplet velocity effect.

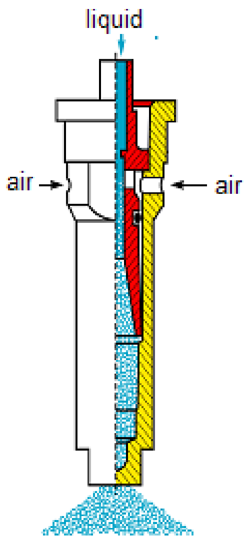

Figure 2.2: Air inclusion nozzle

B. Cone nozzles

Cone nozzles are mainly used on hand-operated sprayers and for orchard sprayers in which spray droplets are projected into the canopy by a blast of air from a fan. Cone nozzles produce a circular spray pattern. There are two important types of cone nozzles: hollow cone and full cone nozzles. The hollow cone of sprayed drops is produced by creating a rotation to the liquid behind the outlet in a chamber. Two or more inlets (round or slotted), which can be an integral part of the swirl plate, create this rotation by directing the pressurised liquid into a whirl chamber. The hollow cone nozzle creates a rotating "cone-shaped" sheet that breaks up into droplets by the process of sheet disintegration as described in section 1.3.1. The rotating thin, cone-shaped edge extends over a large area and therefore produces relatively fine droplets. The full cone nozzle has a very similar design to that of the hollow cone, but its full spraying cone is produced by an additional central hole in the swirl that creates this filled hollow cone pattern (Hardi, 2003).

C. Other nozzle types

Deflector nozzles

Deflector nozzles, also referred to as flood jet, mirror or anvil nozzles, do not provide the uniform coverage as obtained with flat fan nozzles. In these nozzles, a jet of liquid from a circular orifice is impacted onto a smooth plate immediately in front of the nozzle orifice. This type of nozzle is usually operated between 1 and 1.5 bar. The droplets produced by flood jet nozzles are coarse or very coarse and hence it is difficult to spray existing weed foliage uniformly without dripping or run-off. Recently new designs have resulted in more uniform droplet sizes and improvement in pattern uniformity (e.g. Turbo TeeJet).

Twin fluid nozzles

Twin fluid nozzles have been developed for use in crop spraying. These nozzles mix air and spray liquid internally to have larger control of spray quality. The most widely used are Airtec (Figure 2.3, Cleanacres Machinery Ltd) and AirJet nozzles (Spraying Systems Co.®). These nozzles generate droplets by injecting air at an angle onto a jet of liquid from the liquid metering orifice within the nozzle body. They are based on a deflector nozzle and use a compressor to provide air inside the nozzle. With these nozzles, a constant air-liquid pressure is required to maintain a similar droplet size distribution with varying flow (Young, 1991; Combellack & Miller, 1999). Spray quality can be adjusted in the tractor cab without changing nozzles.

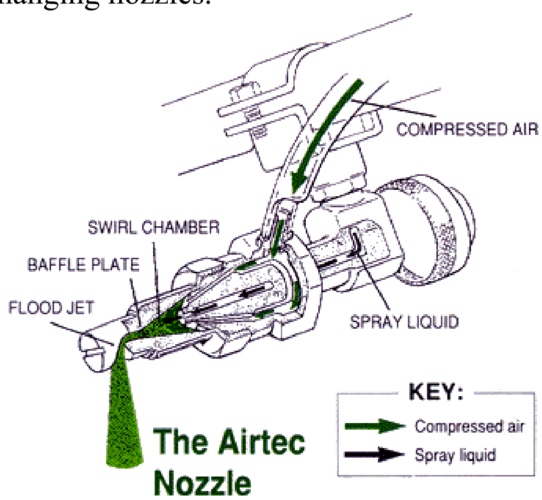

Figure 2.3: Airtec spray nozzle (Cleanacres Machinery Ltd)

Less drift has been reported with these nozzles in comparison with standard fan nozzles, both applying 100 L.ha^{-1} (Rutherford *et al.*, 1989; Miller *et al.*, 1991). Western *et al.* (1989) concluded that for many combinations of liquid and air pressure, the twin fluid nozzle produces less drift than standard flat fan nozzles. However, some combinations producing potentially driftable sprays were identified in cases where air pressure is increased or liquid volume is low. Young (1991) and Miller (1993) suggested that for this type of nozzles, the liquid break-up to form a spray occurs within the nozzle body and hence the emerging spray is more porous and less of an obstruction to an approaching airflow. This leads to less air flowing around the spray structure and has been shown to be a major factor leading to the low levels of drift.

D. Drift reduction results

Field drift measurements (§ 2.3.4) with different nozzle types, boom heights and spray pressures have been carried out by van de Zande *et al.* (2000 b) and Balsari *et al.* (2006) to determine drift reduction potentials of different spray application techniques compared with a reference. An overview of the drift reduction results is presented in Table 2.2. These results are compared with the results from this study in section 5.3.3.

Table 2.2: Drift reduction results of different nozzle-pressure combinations from different field drift studies

Nozzle	ISO nozzle size	Pressure (bar)	Boom height (m)	Drift reduction (%)	Remarks	References
TeeJet XR	02	3	0.5	-185	- Potato crop - Reference =TeeJet XR 110 04 at 3 bar, 0.5 m boom height, 300 L.ha^{-1} - Drift reduction measured at 2-3 m from last nozzle	van de Zande *et al.*, 2000 b
TeeJet DG	02	3	0.5	-29		
TeeJet DG	04	3	0.5	72		
Lechler ID	02	3	0.5	78		
Lechler ID	04	3	0.5	87		
Agrotop XLTD	02	3	0.5	55		
Agrotop XLTD	04	3	0.5	88		
TeeJet TT	02	3	0.5	-145		
TeeJet TT	04	3	0.5	54		
TeeJet XR	03	5	1.0	-104	- Reference = TeeJet XR 110 03 at 5 bar, 0.5 m boom height, 365 L.ha^{-1}	Balsari *et al.*, 2006
TeeJet XR	03	5	0.8	-35		
TeeJet XR	03	5	0.5	0		
TeeJet AI	03	5	1.0	82		
TeeJet AI	03	5	0.8	61		
TeeJet AI	03	5	0.5	92		
Hardi Injet	03	3	0.5	88	- Reference = Hardi ISO F 110 03 at 3 bar, 7.2 km.h^{-1}, 0.5 m boom height, grass	Taylor *et al.*, 1999
Hardi Injet	04	3	0.5	85		

Drift reduction classes: 25-50 % | 50-75 % | 75-90 % | > 90 %

XR, extended range; DG, drift guard; ID, Air-Injektordüsen; XLTD, TurboDrop XL; TT, Turbo TeeJet; AI, air induction; Injet, air inclusion

2.2.1.4. Nozzle classification

Because of the importance of droplet sizes, systems have been developed for classifying agricultural sprays by droplet size. Such classification systems enable regulators, applicators and growers to standardise the description of nozzle systems and thus spray quality. Moreover, it is known that although protocols and equipment for droplet sizing (described in § 2.3.2.2 and § 2.3.2.3) are quite robust, differences in measuring results can be observed depending on functional principle and type of measuring system used. That is why classification systems have been established.

A. BCPC nozzle classification

The British Crop Protection Council (BCPC) nozzle classification scheme was devised during the mid 1980's as a means of standardising the relationship between a variety of measuring systems (§ 2.3.2.2) and describing the entire droplet spectrum generated by hydraulic spray nozzles or other atomizers (Doble *et al*., 1985; Parkin *et al*., 1994; Southcombe *et al*., 1997). The BCPC scheme recognized that different droplet size spectra are sometimes reported for similar sprays measured by different instruments and techniques and for different sampling techniques within an instrument type (§ 2.3.2). The spray classification system divides the quality of sprays into five categories: very coarse (VC), coarse (C), medium (M), fine (F) and very fine (VF). Later on, a sixth category was introduced namely 'extremely coarse' (EC) (Table 2.3).
The scheme was originally developed for defining ground hydraulic application nozzles, however, other nozzle types are now being encompassed by the scheme. The boundaries of the different categories are defined using five nozzle-pressure combinations giving five reference sprays. The results are usually presented as cumulative volume curve as presented in Figure 2.4. Attempts to reduce these curves to a single figure (e.g. *VMD*) introduce inaccuracies (Doble *et al*., 1985).

Table 2.3: BCPC reference nozzles and settings (Southcombe *et al.*, 1997)

Boundary category	Nozzle type	Pressure (bar)	Flow rate (L.min^{-1})
Very fine/fine (VF/F)	Delavan 110 01	4.5	0.48
Fine/medium (F/M)	Lurmark F 11003	3.0	1.18
Medium/coarse (M/C)	Lechler LU 120 06	2.0	1.93
Coarse/very coarse (C/VC)	TeeJet 8008	2.5	2.88
Very coarse/extremely coarse (VC/EC)	80-15	2.0	4.90

Droplet size distributions of test nozzles can be compared to the reference sprays, allowing the spray quality to be determined. This system should enable advisers, users, product suppliers and registration authorities to describe the preferred way in which the product should be presented to the target and to determine the environmental safety of the proposed application. Herbst (2001 a) recommended this classification as an international standard though the sensitivity of the system for coarse droplet size spectra should be increased.

Comparing three different measuring systems, Herbst (2001 a) concluded that although the measuring results in terms of cumulative droplet volume distribution were different, the classification of spray quality using the BCPC nozzle classification scheme gave the same results for almost all tested nozzle types. Issues affecting sampling in conjunction with the

ASAE (now ASABE) scheme were discussed by Maynard *et al*. (1996). Remark that differences increased with droplet size.

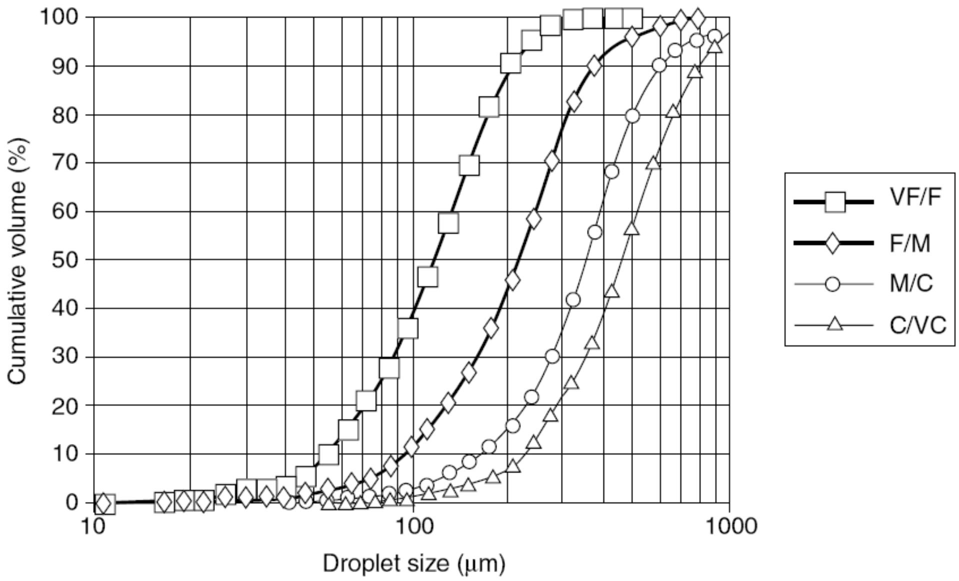

Figure 2.4: A BCPC droplet size reference curve

B. ASAE S572 – Spray nozzle classification by droplet spectra

The American Society of Agricultural Engineers (ASAE) used the BCPC droplet size classification system as a basis for a spray classification system adapted to U.S. agriculture. There are some small differences between the BCPC and ASAE schemes, although the concept is the same for both (Hewitt *et al*., 1998). In accordance with the BCPC classification, ASAE standard S-572 (2004) "Spray Nozzle Classification by Droplet Spectra" has six categories: very fine (VF), fine (F), medium (M), coarse (C), very coarse (VC) and extra coarse (XC). The boundaries of the categories are also defined by the droplet size spectrum from a particular nozzle, flow rate and pressure that is called a reference spray as presented in Table 2.4. Reference nozzle sprays, rather than defined droplet spectra, are used to divide the categories due to differences in the instruments used to measure the droplet size spectra.

Table 2.4: Classification category treshold values for flat fan spray nozzles according to ASAE S572 (2004)

Classification category treshold	Nozzle spray angle (°)	Reference flow rate ($L.min^{-1}$)	Reference operating pressure (kPa)
Very fine/fine (VF/F)	110	0.48	450
Fine/medium (F/M)	110	1.18	300
Medium/coarse (M/C)	110	1.93	200
Coarse/very coarse (C/VC)	80	2.88	250
Very coarse/extra coarse (VC/XC)	65	3.22	200

This standard can be used to describe the output of specific nozzle-pressure combinations under defined conditions by comparing the droplet spectrum of the test nozzle to the standard curves from the reference sprays. If the cumulative droplet spectrum curve for the test spray falls entirely between two reference sprays or entirely outside the finest or coarsest reference spray, it is then placed in the appropriate category. If any part of the test nozzle curve (between $D_{v0.1}$ and $D_{v0.9}$) crosses any reference spray curve, then the nozzle is placed in the finer of the two categories. Remark that all the BCPC reference nozzles fulfil the ASAE specifications except for the VC/EC BCPC reference nozzle. Issues affecting sampling in conjunction with the ASAE scheme were discussed by Maynard *et al*. (1996). For more details, the standard itself should be consulted (ASAE S572, 2004).

Although Womac *et al*. (1999) and van de Zande *et al*. (2002 b) called attention to the importance of a detailed specification of reference nozzle, this is not the case in the ASAE S572 standard in contrast to the BCPC nozzle classification. Nozzles from different manufacturers of alternative designs and materials do affect their performance despite their consistent specifications for spray pressure, flow rate and top angle. Womac (2000) even measured small variations among 'identical' reference nozzles which raises the issue of nozzle manufacturing uniformity.

2.2.1.5. Spray quality and biological efficacy

Droplet size, velocity and direction influence the penetration and deposition of droplets in the plant canopy (Brunskill, 1956). Hislop (1987) concluded that the efficacy of a particular pesticide is often dependent upon droplet size. A high coverage of the target is usually best achieved with small droplets (Cawood *et al*., 1995) because finer droplets give a proportionally greater coverage for any given level of spray deposit.

Large droplets impact on the upper parts of the plants, whereas small droplets mixed with large droplets may penetrate the canopy to reach the lower parts of the plants as well as the more accessible sites. In other cases, large droplets hitting the top leaves cause movement of the leaves. Some of these large droplets splash on impact and are redistributed as smaller droplets further down in the plant canopy. When fine sprays are applied, a higher coverage on the top leaves may be reached but with reduced crop penetration (Western *et al*., 1985).

Many researchers recognise the need for research to determine the biological optimum droplet size for herbicides, fungicides and insecticides. Some decades ago, very small droplets were recommended. Himel and Uk (1975) suggested that the optimum size is within the range 15-80 μm for most crop pests. The optimum size for the control of flying pests may be 5-25 μm (Mount, 1970). More recently, bigger optimum sizes of droplets have been defined for different applications. Droplet sizes smaller than 60 μm are often used for spraying flying insects or for greenhouse spray applications. Droplet sizes between 60 and 200 μm are commonly used for pest and pathogen control on targets such as plant leaves. Droplets bigger than 200 μm are typical for herbicide applications to ensure deposition on the ground (Hewitt, 1997). Droplets larger than 400 μm might have a tendency to bounce off the vegetation (Bouse *et al*., 1990). The optimum droplet size for delivery to a target is not always the same as that for achieving the best results on the target.

Permin (1983) studied the effect of spray quality on biological performance after foliar application of herbicides and fungicides (Permin *et al*. 1992). They found no significant differences in biological effect between different nozzle types although there were differences in deposit amounts. The same results were found by Klein and Johnson (2002), they concluded that different drift-reducing nozzles all provided a good efficacy. Others found that an increase in droplet size resulted in a decrease in spray efficiency like Munthali (1984) and Alm *et al*. (1989).

When using air inclusion nozzles, there is a concern that the larger droplets may induce an increased run-off and reduce the efficacy of foliar acting pesticides (Wolf, 2002). At this moment, little research has been carried out to evaluate biological performance of air inclusion nozzles. Powell *et al.* (2002) tested a range of air inclusion nozzles and concluded that particularly in the early growing stage of black grass, a reduction in efficacy may be observed when using air inclusion nozzles. Research by Jensen (1999), showed that herbicide efficacy can be reduced with low volume air inclusion nozzles, spraying larger droplets, when spraying small targets. Whisenant *et al.* (1993) concluded that increased spray volumes are necessary to maximize the efficacy of insecticides when spraying large droplets. Wolf (2002) found that air inclusion nozzles can provide similar performance to conventional sprays provided the operator is given information on how to make initial nozzle selections and optimize their performance.
Frieβleben (2004) investigated the relation between spray quality and biological efficacy based on available data in fruit and arable growings. He concluded that coarse droplet applications do not have a detrimental impact on efficacy. Similar results were found by Heinkel *et al.* (2000), Shaw *et al.* (2000) and Wolf (2000; 2002). The principal factors which have an impact on efficacy are choice of product, timing and weather conditions. Of course, this assumes that the technique used is in line with requirements in all essential parameters.

2.2.2. Sprayer factors

2.2.2.1. Spray boom height and boom configuration

Boom height is an important factor in reducing drift losses. Operating at a spray boom height as close as possible to the vegetation, without sacrificing the uniformity of the spray pattern, is a good way to reduce drift (Göhlich, 1983; Ozkan, 1998; Teske & Thistle, 1999).
De Jong *et al.* (2000) investigated the effect of boom height for conventional and for air-assisted spraying. Lowering boom height as well as the use of air-assistance resulted in a statistically significant sedimenting and airborne drift reduction compared to the conventional reference spraying (TeeJet XR 110 04 nozzles, 300 $L.ha^{-1}$, no air-support, 0.50 m boom height) as presented in Table 2.5. These figures are confirmed by the drift model developed by Holterman and van de Zande (1996) and Holterman *et al.* (1997). Similar results were found by Combellack *et al.* (1996).

Table 2.5: Drift reduction percentages for different boom heights with and without air assistance at distances from 2-3 and 1-4 m from the last nozzle (de Jong *et al.*, 2000)

		Sedimenting drift reduction (%)		Airborne drift reduction (%)
Boom height (m)	Air assistance	2-3 m distance	1-4 m distance	
0.70	No	-116	-62	-82
0.70	Full	57	45	84
0.50	No	0*	0*	0*
0.50	Full	90	75	87
0.30	No	56	58	24
0.30	Full	95	86	91

* Reference

Correct boom height for each nozzle type is determined by nozzle spacing and spray angle. Wide-angle nozzles can be placed closer to the ground than narrow-angle nozzles but they also produce smaller droplets. Modification to nozzle number, type and orientation is usually required to maintain an even spray pattern when lowering the spray boom. As the distance between the spray nozzle and the target area increases, the impact of wind velocity and therefore drift increases too. Moreover, wind speed increases with height. With lower boom heights, the initial droplet speed may be large enough for the droplet to reach its target before drift occurs but adequate boom stabilisation is necessary. Spray boom movement results in deposit variations along the swath but also in increased drift when nozzles swing above their mean position. Stallinga *et al*. (2004) found that lowering the boom height from 0.50 to 0.30 m in combination with reducing nozzle spacing from 0.50 m to 0.25 m and using smaller nozzles sizes, still reduced drift significantly.

Besides the effect of boom height, the spray boom configuration has an effect on the risk of spray drift. Murphy *et al*. (2000) compared three different boom sections: a standard boom, a deep boom (for maximum air blockage) and a profile boom (for reduced vertical dispersion). Moreover, the effect of variations in spray plume porosity to an airstream was investigated by varying spray quality and nozzle distance. Maximum airborne drift occurred at a nozzle spacing of 0.5 m with all spray qualities. As expected, drift decreased as sprays changed in quality from fine to coarse. Although boom section designs can affect drift, the effect of boom section on the amount of spray drift was much less than the effect of spray quality. Compared to a standard boom section, a deep section increased drift by 10% while a profile section reduced drift by 7%.

2.2.2.2. Driving speed

Relatively few studies have been carried out on the effect of forward speed on spray drift although tractor and sprayer movement together with its induced air turbulence and boom movement will affect the air circulation. Increasing driving speed can cause the spray to be diverted back into upward currents and vortexes behind the sprayer which trap small droplets and can contribute to drift. Taylor *et al*. (1989) measured the drift from boom sprayers at forward speeds of 4.0, 7.0 and 10 km.h^{-1} and found an increase in airborne spray drift downwind of approximately 4% as speed increased from 4.0 to 7.0 km.h^{-1} and 90% for a speed increase from 7.0 to 10.0 km.h^{-1}. Miller and Smith (1997) measured an increase in airborne spray drift in the field of approximately 51% for a forward speed increase from 4.0 to 8.0 km.h^{-1} and by 144% when the speed was further increased to 16.0 km.h^{-1}. The analysis showed no difference between sprayer speeds of 8 and 12 km.h^{-1}. Measurements in a wind tunnel also showed that higher forward speeds gave higher levels of drift (Miller and Smith, 1997). Van de Zande *et al.* (2005 a) also measured an increase in spray drift from 29 up to 51% when driving speed increased from 6 to 12 km.h^{-1} using conventional XR 110 04 nozzles.

Based on a CFD simulation study, Tsay *et al*. (2002 a) concluded that local relative velocity plays an important role in controlling the drift potential of a moving sprayer. The higher the local relative velocity, the greater the drift potential. When the sprayer moves upwind, drift potential increases slightly with increased travel speed. However, when the sprayer moves downwind, drift potential decreases inversely with increased travel speed, as long as travel speed is less than wind velocity.

2.2.2.3. Air assistance

The use of air-assisted spraying systems is not a new concept but one that has been recently reconsidered. According to Hislop (1991), the first air-assisted sprayer was probably developed in France around 1885 for vine applications. Conceptually, an air-assisted spraying system is a specially designed sprayer capable of supplying airflows to carry and disperse sprays formed by atomizers. Small droplets quickly lose momentum imparted by a nozzle system and tend to quickly assume the speed and direction of ambient airflow. If the air movement around the sprayer can be altered so that it is directed towards the target, it is possible to reduce drift (Young, 1991; van de Zande *et al*., 2000 a) as well as increasing deposition towards the target. This is the basic principle behind the design of air-assisted sprayers. This principle also prevents formation of a raising spray cloud of small droplets that is seen in conventional practice. Moreover, in some cases the nozzles and the air stream can be angled and adjusted depending on wind and driving direction.

Nowadays, commercial air-assisted spraying systems can be separated into two groups based on the approach of introducing spray into the air stream (Tsay *et al*., 2002 b). For the first group, such as the Hardi Twin system (Figure 2.5), atomizers are outside of the air stream but are directed into the stream at a specific angle. Sprays ejected from the atomizer intercept the air stream at some point above the canopy. The air stream and atomizer can be independently adjusted to achieve different configurations. For the second group, such as the Spray-Air system (Spray-Air U.S.A., Figure 2.5), atomizers are mounted within the air stream. Since atomization is affected by the air-stream velocity, the air velocity setting is critical to achieve desired droplet size spectra. To distinguish between these two air-assisted systems, hereafter the first group is referred to as *restricted air-assisted spraying* and the second group as *air-shear spraying* as reported by Tsay *et al*. (2002 b).

A. Restricted air-assisted spraying

Caught and delivered by air currents, droplets from restricted air-assisted spraying systems are protected to some extent from wind. Therefore, restricted air-assisted spraying systems may reduce spray drift considerably (Quanquin, 1992; Quanquin, 1995; Taylor *et al*., 1989; Young, 1991). Among those studies, Taylor *et al*. (1989) indicated that angling the air curtain forward with flat-fan nozzles on a Hardi Twin system can reduce drift over stubble by 60%. Increasing spraying speed increases spray drift when air assistance is not used, but drift remained nearly constant for a given nozzle when air assistance is available. However, Young (1991) reported that the benefit of the Twin System air curtain decreased with increasing droplet size. Although most experiments showed that restricted air-assisted spraying reduced spray drift, some researchers reported contrary results.

Cooke *et al*. (1990) compared spray drift by using hydraulic nozzle sprayers and a restricted air-assisted sprayer (Deganya). Even with better droplet distribution uniformity and equal spray deposition, the restricted air-assisted sprayer generally produced more drift when compared to hydraulic sprayers. They concluded that drift can be decreased unless parameters such as air speed and spray release height above the target crop are optimized.

Hislop *et al*. (1993) reported that air assistance substantially reduced spray drift at a wind speed of 4 $m.s^{-1}$ in a wind tunnel, but significantly increased small amounts of spray drift at wind speeds of 1 and 2 $m.s^{-1}$ with air assistance 45° forward or backward to the direction of travel. Howard and Mulrooney (1995) discussed concerns related to off-target drift and indicated that restricted air-assisted sprayers have greater potential for particle drift on bare ground when compared to conventional row sprayers, especially when lower rates of carrier volume and higher air speeds are used.

Figure 2.5: Some air-assisted sprayers (a) Hardi Twin (b) Degania (c) Spray-Air

To take advantage of the benefits of restricted air-assisted spraying, some researchers investigated optimum settings for the air jet. Panneton *et al*. (1996) isolated the effects of air speed (0 to 36 $m.s^{-1}$), airflow rate (0 to 1.3 $m^3.s^{-1}.m^{-1}$), and air jet orientation (-10.2° to 40.2°) on leaf coverage based on a study of restricted air-assisted spraying. Optimum spraying conditions based on providing protection to all leaf undersides for broccoli and potatoes on average were: airflow of 0.94 $m^3.s^{-1}.m^{-1}$, air speed of 31 $m.s^{-1}$ and air jet angle of 22°.
Similarly, Ringel *et al.* (1991) (reported by Pompe and Holterman, 1992) studied the effect of air release angle (20° forward, vertical, and 30° backward) and air speed (0, 16, and 28 $m.s^{-1}$) on emission to the air and ground and depositions on winter wheat using a Hardi Twin system sprayer. They found that emissions to the air and ground were most effectively reduced when the air was released with a forward angle of 20° at the highest air speeds. This agrees with results of Taylor *et al*. (1989) and May (1991), which suggested that a rearward-angled sprayer boom resulted in more drift than a downward-angled sprayer boom.

Van de Zande *et al*. (2002 a) studied the effect of air assistance on the amount of drift in potato crops. Drift was evaluated at a distance of 2 to 3 m from the last nozzle. The amount of extra drift reduction using air assistance varied from 45 to 90% depending on the nozzle type as presented in Table 2.6.

Table 2.6: Drift reduction percentages using air assistance for different nozzle types at 3 bar (van de Zande, 2002)

Nozzle	ISO nozzle size	Drift reduction (%)[1]	Nozzle	ISO nozzle size	Drift reduction (%)[1]
TeeJet XR	02	78	Lechler ID	04	67
TeeJet XR	04	71	Agrotop XLTD	02	47
TeeJet DG	02	62	Agrotop XLTD	04	67
TeeJet DG	04	53	TeeJet TT	02	90
Lechler ID	02	45	TeeJet TT	04	74

[1] Drift reduction compared with spraying without air assistance with the same nozzle type; XR, extended range; DG, drift guard; ID, Air-Injektordüsen; XLTD, TurboDrop XL; TT, Turbo TeeJet

B. Air-shear spraying

In literature, only little information can be found about air-shear spraying and drift. To evaluate the performance of air-shear spraying, Campbell and Thill (1995) compared wild oat control by using an air-shear sprayer, a conventional sprayer, and a conventional sprayer with air-assist added. They found that efficient control of wild oat and the ability to reduce herbicide rates by using an air-shear sprayer depended on the herbicide. Drift was not increased with the air-shear sprayer compared to the conventional sprayer.

2.2.2.4. Asymmetric edge nozzles

Asymmetric edge nozzles have an outlet orifice oriented sidewards which results in an off-centre spray pattern as presented in Figure 2.6. These nozzles are used at the end of the spray boom around the perimeter to protect sensitive areas. Using the drift model IDEFICS (§ 2.4), Holterman and van de Zande (1996) found drift reduction percentages varying from 30 to 50%.

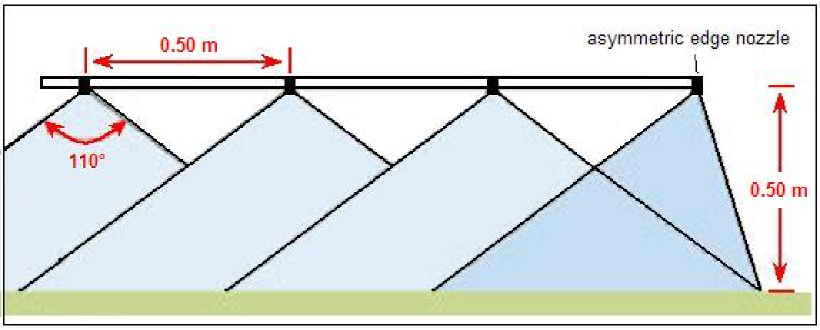

Figure 2.6: The use of an asymmetric edge nozzle

2.2.2.5. Shielded sprayer booms

Wind is a primary factor in spray drift. Therefore, some researchers have worked on developing attachments to overcome the influence of wind and to provide a barrier that physically intercepts the drifting droplets. Use of protective shields to decrease spray drift was first recommended by Edwards and Ripper (1953). Their "Nodif" boom reduced drift by 46% to 85% compared with an unshielded sprayer, depending on nozzle tip size, operating pressure, and wind speed. Drift reduction information from different references was discussed by Tsay *et al*. (2002 c) and summarized in Table 2.7.

Courshee (1959) indicated that a deflector placed downwind from the spray, at a height at which the drift would impinge on it, was effective in reducing drift when the nozzle was low. This drift reduction was of less value when the nozzle was high and when the gap between the crop and the deflector was larger. Many other researchers (Smith *et al.*, 1982 a; Lake *et al.*, 1982; Ford, 1984; 1986; Göhlich, 1985) have used solid or gauze mechanical shields. The shields decreased drift deposits to about 62 to 85% of downwind deposits. Rogers and Ford (1984; 1985) and Rogers and Jackson (1987) developed a shrouded sprayer (the “Windproof”) for use in windy conditions. Their studies and those of Fehringer and Cavaletto (1990) found drift reduction of 45 to 65% with the shrouded sprayer compared to an open-boom sprayer. Ford (1984) used air jets to reduce drift deposits to about 95% of conventional boom sprayer drift deposits. However, Miller (1988) found that air jets did not reduce drift due to reflection of the forced air from the ground. Field trials by Maybank *et al*. (1991) with shielding of individual nozzles on a spray boom using WindCone (Brandt Industries, Ltd., Regina, Saskatchewan, Figure 2.7) showed that in a wind speed range of 4.16 to 8.33 $m.s^{-1}$, the shields efficiently reduced off-target spray deposit from 80 02 nozzles by a factor varying between 1.7 and 3.0.

Table 2.7: Drift reduction information from shielded sprayer booms from different references (Tsay *et al.*, 2002 c)

Shield description	Field or laboratory experiment	Amount of drift reduction (%)	Reference
“Nodif” boom	Laboratory	46 to 85	Edwards and Ripper (1953)
Mechanical shielded boom	Laboratory	up to 70	Smith *et al*. (1982 a)
Aerofoil	Laboratory	62	Lake *et al*. (1982)
Power-aspirated winnower	Field	95	Ford (1984)
Gauze shroud	Field	up to 80	Ford (1984)
Double-foil shield	Field	67	Göhlich (1985)
Porous shroud	Field	85	Ford (1986)
“Windproof” sprayer	Field	45 to 65	Fehringer and Cavaletto (1990)
WindCone (Brandt Industries, Ltd.)	Field	41 to 67	Maybank *et al*. (1991)
Air-assisted spraying with a simple bluff plate	Field	71 to 80	Furness (1991)
Protective cones	Field	33	Wolf *et al*. (1993)
Solid or perforated shielding + lower boom height	Field	48 to 84	Wolf *et al*., (1993)
Spray-boom shields	Laboratory	13 to 59	Ozkan *et al*. (1997)
Symmetrical triple-foil shield	Laboratory	61	Sidahmed *et al*. (2004)
Symmetrical double-foil shield	Laboratory	55	Sidahmed *et al*. (2004)
Double-foil shield	Laboratory	48	Sidahmed *et al*. (2004)

Furness (1991) compared two systems, a simple bluff plate in front of the nozzles and a rotary sleeve atomizer in the centre of a shrouded axial fan, mounted on a single spray vehicle for high-speed (5.6 to 11.1 $m.s^{-1}$), low-volume (11 to 15 $L.ha^{-1}$), air-assisted spraying application. He found that axial fans are of little value for improving spray deposition, while air-assisted spraying with a bluff plate, when compared to non-air-assisted treatments, increased deposits by 4 and 2.5 times for both 0.5 m tall wheat and sunflower plants, respectively. On sunflowers, using the bluff plate, approximately 60% of the spray was deposited on lower leaf surfaces, while without the bluff plate and with a conventional boom, little or no spray was deposited on lower leaf surfaces.

Wolf *et al*. (1993) conducted field trials on the effectiveness of commercially available shields in reducing off-target drift from field sprayers. They found that use of protective cones with ISO 80 01 nozzles and without lowering the boom reduced airborne drift by 33%, while a 48 to 84% drift reduction was accomplished with the combination of solid or perforated shielding and lowering the spray boom from 0.45 to 0.40 m. Off-target drift increased with increasing wind speeds for all sprayers, but the increase was less for shielded sprayers. In addition, high wind speeds, lower carrier volumes and finer sprays, 110° tips, and solid shields tended to decrease on-swath deposit uniformity, while perforated shields or cones did not affect deposit uniformity. They suggested that the effect of air turbulence under solid shields on deposition variability needs to be further investigated.

Figure 2.7: Different types of shielded sprayer booms: (a) WindCone (Brandt Industries, Ltd.) (b) Flexicoil (Ag Shield Mfg) (c) Släpduk (Viby Teknik)

French *et al*. (1993) conducted wind tunnel trials to determine drift potential of both unshielded and commercially available shielded-boom sprayers. Results from these wind tunnel tests were similar to those obtained in field trials by Wolf *et al*. (1993). A shield, like the Rogers and Flexicoil shields (Ag Shield Mfg., Figure 2.7), that will break up the trailing vortices caused by the flow around the fan-shaped spray, appeared most effective in reducing drift potential of fine droplets. Effectiveness of porous shrouding on sprayer booms for reduction of wind velocity in the vicinity of a spray nozzle was investigated by Cenkowski *et al*. (1994). They indicated that a steeper boom shape allowed for greater air penetration and less deflection over the boom, but it was less effective for velocity reduction. They also noted that the use of airfoils or impermeable shielding on the entire front side appeared most effective because there was a significant wind speed reduction (> 50%), and airflow was directed down toward the crop.

Ozkan *et al*. (1997) conducted wind tunnel experiments and computer simulations to determine the effect of several spray-boom shield designs and “low-drift” nozzles on spray drift. All nine shields tested during this study effectively reduced spray drift. Even the least effective shield design produced a 13% improvement in deposition of spray on the ground. A double-foil shield produced the best spray deposit improvement (59%) compared to the same nozzles spraying without the shield. A simulation using a CFD model (FLUENT) showed that the shield did not affect drift of droplets with diameter less than 50 μm. These droplets left the wind tunnel without depositing on the floor. Similar CFD simulation studies were performed by Tsay *et al*. (2002 a; c).

Sidahmed *et al*. (2004) carried out a series of wind tunnel experiments with different types of (symmetrical) multi-foil shields. Drift reduction percentages varied from 48 to 61% depending on the type of shield as presented in Table 2.7.
Enfält *et al*. (2000) developed a new application technique named Släpduk™ (Viby Teknik, Figure 2.7) which reduces drift and increases crop penetration and deposition. It consists of a springy parallelogram on which the nozzles are mounted with angled backwards. On the lower part of the parallelogram, a plastic sheet is mounted. This technique gives a good spray distribution and enables a low boom height. In high crops, it works as a crop opener. Drift reduction percentages varied from 26 to 84% compared to a conventional spraying depending on the crop type and spray quality. Similarly, van de Zande *et al.* (2005 b) measured spray drift reductions using the Släpduk™ system (at a boom height of 0.20 m and with a nozzle distance of 0.33 m) of at least 75% using standard flat fan nozzles (XR 110 015) and up to 99% using a venturi flat fan nozzles (AI 110 015) compared to a standard field sprayer with XR 110 04 nozzles.

In general, shielded spray booms have the ability to reduce drift and can make an important contribution to efforts leading to reduced pesticide inputs into the environment although the results vary considerably from one study to another. However, shields do not eliminate drift, and drift losses are still a function of the coarseness of the spray and environmental conditions. Moreover, covered booms do not permit applicators to check the nozzles during spraying and problems with spray boom stability, folding up the spray boom, and spray liquid dripping from the shield may arise. Additionally, the cost of the sprayer increases. Because of these reasons, shielded sprayer booms have not been well accepted by farmers.

2.2.3. Spray liquid properties

It has been established for many years that properties of the spray liquid, which depend upon formulation and adjuvants, can affect the quality of the spray produced by agricultural nozzles (Dombrowski *et al*., 1960; Ford & Furmidge, 1967; Miller & Butler Ellis, 1997; Butler Ellis *et al*., 2001). This clearly has important consequences when controlling the application process to optimise pesticide inputs and minimize off-target contamination. Spray formation is a very complex process mainly influenced by liquid density, surface tension and viscosity (Dombrowski & Johns, 1963; Hewitt *et al*., 2000). Other authors suggest that other liquid properties, such as surface rheology (Butler Ellis *et al*., 1997) and encapsulation effects (Hewitt *et al*., 2000), may also be important. Moreover, the effect of the physical properties of the liquid on the break-up process cannot be considered separately from the mechanical factors involved in the construction of the device or the hydrodynamic factors involved in the passage of the liquid through the spray equipment and in particular the spray nozzles (Butler Ellis & Tuck, 1999). That is why the influence of the properties of the spray liquid on spray droplet size is still not well understood. Different hydraulic spray nozzles (like hollow cone, pre-orifice and deflector nozzles) have similar break-up mechanisms to standard flat fan nozzles because they all have a liquid sheet which rapidly expands, thins and disintegrates into droplets (Butler Ellis & Tuck, 1999). Only air induction nozzles are more sensitive to changes in the physical properties of the spray liquid than conventional nozzles and the changes do not necessarily follow the same trend (Miller & Butler Ellis, 2000).
Theories of liquid sheet break-up that predict spray droplet size (Lefebvre, 1989) are appropriate only for pure liquids undergoing break-up through oscillation and not necessarily for other types of solutions.

2.2.3.1. Liquid density

Drop size of the spray is positively correlated to the density of the spray liquid. A nozzle-pressure combination producing an aqueous spray with a volume median diameter (*VMD*) of 200 µm will produce a *VMD* of 130-140 µm with a light hydrocarbon oil with a density of about 850 kg.m^{-3} (Elliott & Wilson, 1983). Other measurements indicate that there are only insignificant differences between water and water with different active ingredients (Hardi, 2003).

2.2.3.2. Surface tension

Surface tension is known to be a factor in determining droplet size, whichever spray formation mechanism is predominant (Lefebvre, 1989). Pesticides are usually formulated in such a way that they can be dispersed readily in water to provide a uniform spray dispersion. Surfactants are commonly used to stabilise the dispersions of liquid or solid particles in the diluent water. They will adsorb at the air/water interface to reduce the surface tension of the spray liquid. A reduction in the surface tension of a spray fluid produces a spray with smaller drops and an increase in drift (Sarker *et al*., 1997).

Surface tension varies inversely with temperature (Nordbo, 1990). Other measurements showed that different additives have the same low static surface tension (31 mN.m^{-1}), independent of type of additive and of concentration (Hardi, 2003). Among others Selcan and Göhlich (1982) have found that *VMD* was increased when surface tension was increased. This should not lead to the conclusion, that low surface tension means decreased *VMD* in general, as oils have a low surface tension and increase the *VMD*. Berger (1988) has found that the static and the dynamic surface tension can be entirely different, depending on concentration, additive, water hardness and time after mixing. Spanoghe *et al.* (2004) indicated the importance of nozzle type in the relation between droplet size spectrum and surface tension. Measurements on adjuvants using the maximum bubble pressure method (Hall *et al*., 1993; Murphy *et al*., 1993) and oscillating jet method (Brazee *et al*., 1994) have shown that many adjuvants reduce the surface tension at a rate dependent on concentration.

2.2.3.3. Viscosity

The effect of viscosity on drop size is more complex than the effect of surface tension. The break-up of the liquid sheet varies according to the magnitude of the Reynolds number (*Re*). The Reynolds number is a non-dimensional parameter determining the relative magnitude of inertial and viscous forces of the stream and is defined by:

$$\mathrm{Re} = \frac{v_l . d}{\upsilon_l} \qquad (2.1)$$

Where

v_l = Liquid velocity (m.s^{-1}),
d = Droplet diameter (m),
υ_l = Kinematic viscosity of the liquid (m².s^{-1}).

When *Re* is high, the flow is turbulent and changes in viscosity have no effect on *VMD*. In the intermediate range of *Re*, when turbulent flow is giving way to laminar flow, an increase in viscosity causes a decrease in *VMD*. In the low range of *Re*, an increase of viscosity increases *VMD* (Elliott & Wilson, 1983).

When measuring the viscosity on one of the most viscous known mixes of pesticides (phenmedipham + metamitron + a mineral oil) the increase in viscosity compared to water is 12%. The same difference can be obtained by a decrease in temperature of the spray liquid of 5°C (Hardi, 2003). Sarker *et al*. (1997) found that increasing viscosity marginally increased drift.

2.2.3.4. Spray additives and formulation

A large number of materials (surfactants, oils, polymers and other macromolecules, etc.) have been recommended as *additives* to pesticide sprays to improve their performance in a variety of ways. Many of them are claimed to minimize the drift hazard, usually by increasing the drop size (Bouse *et al.,* 1990; Ozkan *et al*., 1993; Sanderson *et al*., 1993; Salyani & Cromwell, 1993; Hanks, 1995; Zhu *et al*., 1997; Nicholls *et al*., 2004) by changing liquid properties such as viscosity (Elliott & Wilson, 1983). Differently formulated pesticides may react individually with spray additive. Hence, the use of a drift-reducing agent is not a simple matter of applying an additive and reduce drift. The suitability of the spray additive must be tested with the individual pesticide spray for each specific spray application technique. A literature review about the effect of different classes of adjuvants on spray droplet spectra is presented by Spanoghe *et al.* (2007 a).

Alness (1986), Maas and Krasel (1988) and Sparks *et al*. (1988) found that different additives showed positive effects in the form of reduced droplet size spectrum and reduced drift. This may have several consequences: the spray angle is often reduced at the same time and the liquid distribution is affected, especially when the mixing directions are not followed closely Chapple *et al*., 1993). Some drift-reducing agents are sensitive to shearing by the pump and may even end up producing smaller droplets than if the product had been left out (Bouse *et al.,* 1988; Chapple *et al*., 1993; Sanderson *et al*., 1993; Reichard *et al*., 1996; Zhu *et al*., 1997; Hewitt *et al*., 2000). Combellack *et al*. (1996) concluded that emulsifiable oil adjuvants produced less drift than an ethoxylated alcohol surfactant. Hanks (1995) found that effectiveness of adjuvants decreased as air pressures increased. Spanoghe *et al*. (2004) found an important effect of the type of adjuvant and its concentration on droplet spectra. Different authors also noted an effect of spray additive on the spray pattern (Ozkan *et al*., 1993; Miller & Butler Ellis, 2000). Klein and Johnson (2002) and Nicholls *et al*. (2004) concluded that air speed and nozzle selection have a greater influence on initial droplet size than the addition of adjuvants.
The ASAE and the American Society for Testing and Materials (ASTM) are looking at test methods for assessing the performance of drift control additives which may exhibit different behaviours depending on the adjuvant, tank mix partners, agitation and application nozzle (Hewitt *et al*., 1999).

Formulation is an important factor in determining spray formation with a given design of nozzle i.e. whether the formulation is water-soluble or whether it forms an inhomogeneous emulsion or dispersion, such as emulsifiable concentrates or emulsion in water.
Butler Ellis and Tuck (1999) investigated formation of sprays by five hydraulic nozzles in combination with seven spray liquids. All spray liquids had similar spray formation mechanisms, liquid sheet length and spray volume distribution patterns through each of the nozzles. However, droplet sizes were not the same for all the nozzles, with the hollow cone and pre-orifice nozzles showing substantial differences. Different other researchers carried out similar studies like Mueller and Womac (1997), Nicholls *et al*. (2004), Stainier *et al*. (2006 a).

Butler Ellis *et al*. (1997) and Butler Ellis and Bradley (2002) showed that emulsion spray liquids cause early sheet break-up, larger droplets and less drift, while aqueous surfactant solutions cause later sheet break-up, smaller droplets and more drift. The effect of formulation on droplet size was also dependent on nozzle design and wind speed. Moreover, it has been shown that the velocity of droplets can also be influenced by the physical properties of the spray liquid. For a given size of droplet from a flat fan nozzle, the mean vertical velocity, averaged over the cross section of the spray is reduced with aqueous solutions and increased by emulsions (Butler Ellis *et al*., 1997), and consequently the mean liquid velocity changes in the same way (Miller *et al*., 1995 a). This change in velocity can have implications for both spray drift and retention on the target although the same effect may not be seen with all nozzle types.

2.2.4. Climatic conditions

Bird *et al*. (1996), Miller (1993) and Bache and Johnstone (1992) provide reviews of research on locally measured average meteorological effects on drifting spray. Moreover, Bird *et al*. (1996) noted the difficulty of comparing different studies due to an inability to isolate and correct for weather differences. Different meteorological parameters might have an influence on the amount of spray drift such as wind speed and direction, turbulence, atmospheric stability, temperature and relative humidity.

2.2.4.1. Wind speed and direction

Different studies have shown that wind speed has an important influence on the amount of spray drift (Combellack *et al*., 1996) and even dominates drift in the near field (Yates *et al*., 1967; Maybank *et al*., 1978; Crabbe *et al*., 1994). Threadgill and Smith (1975) suggested that the most important factors in drift deposit processes were the droplet size, atmospheric stability and wind speed (vertical and horizontal components), influencing the transport and deposition of droplets in sectors adjacent to the application area.

Drift is strongly positively correlated to wind speed but drift can also occur under highly stable (inversion) conditions (§ 2.2.4.3). Strongly stable atmospheres often form under low wind speed conditions, spraying in a light breeze is therefore ideal.
A number of spray drift studies in the field and in wind tunnels have shown an approximately linear relationship between spray drift and wind speed (Gilbert & Bell, 1988; Western *et al*., 1989; Hobson *et al*., 1990). Many such relationships do not go through the origin and the intercept may be a function of the downwind sampling techniques commonly used. Phillips and Miller (1999) who conducted research in wind tunnels with static nozzles in the field, found airborne spray volume measured downwind of a spray nozzle increased approximately linearly with wind speed.
A decrease in wind speed usually occurs between late afternoon and night as a consequence of the increased stability of the atmosphere caused by the cooling of the underlying ground. Meteorological reports of wind usually relate to a height of 10 m. The wind speed at other heights above the ground at neutral stability conditions (i.e. when the vertical temperature gradient follows the dry adiabatic lapse rate $\Gamma \approx -1$ °C/100 m) can be predicted using the logarithmic wind law (formula 1.5).

Besides the wind speed, it is important to consider the wind direction at application in order to avoid spray drift damage. If possible, sprays should be applied when the wind direction is away from sensitive areas avoiding high wind velocities. A commonly cited wind speed limit of between 3 and 15 $km.h^{-1}$ is proposed as drift-mitigating strategy (PISC. 2002). It should be noted that other factors (e.g. turbulence, humidity, etc.) also heavily influence the movement of droplets.

In considering the field measurement of drift, it is important to be aware of the variation of wind conditions with time (during an experimental run and from run to run) and with height above the ground or crop surface as expressed by formula 1.5 (Miller, 1993). That is why the wind conditions experienced during a practical drift measurement must be defined. This can be achieved by either:

- Monitoring the atmospheric conditions during the experiment,
- Using a comparative twin-tracer technique in which spray is released from both test and reference system simultaneously (Courshee, 1959; Bode *et al*., 1976; Johnstone, 1977; Gilbert & Bell, 1988).

2.2.4.2. Turbulence

Goering and Butler (1975) found that besides horizontal wind speed and temperature, air turbulence affects drift as well as the spraying pressure. The dispersion of spray droplets increases with increasing turbulence intensity and drift will be spread out more in the vertical and horizontal plane. Turbulence intensity may be defined as the ratio of the root mean square of the turbulent velocity fluctuations and the mean wind speed.
Turbulence is created in two ways:

1. *Dynamic turbulence* – Friction of the surface slows down the air near it, and this usually causes overturning and mixing of the air (dynamic turbulence). The average size of turbulent eddies increases with increasing height. The extent of this turbulence is also determined by the roughness of the surface. A stand of trees or a tall crop will generate greater turbulence for a given wind speed than an area of mown grass.

2. *Thermal or atmospheric turbulence* – Thermal or atmospheric turbulence or free convection is caused by the fact that heated air is less dense than the surrounding cooler air and tends to rise. When a surface is warmed by sunshine, the air in contact with it also becomes heated and tends to rise. This increases the dynamic turbulence already existing in the overlying air.

Turbulence values are approximately 0.1 over most agricultural crops, but can be less than 0.05 over bare ground in stable conditions and may rise to 0.15 or 0.2 over forests in unstable conditions (Pasquill & Smith, 1983). Turbulence intensity controls the dispersion rate of the spray cloud. With increasing turbulence intensity, the peak deposit is higher and closer to the source. Unfortunately, the expansive nature of turbulent flow also tends to disperse a low concentration of very small droplets into the atmosphere and at extended distances downwind.

2.2.4.3. Atmospheric stability

Atmospheric stability is a term used to describe the vertical movement of air in the atmosphere and is associated with the temperature gradient in the planetary boundary layer. The effect of atmospheric stability is illustrated in Figure 2.8. This figure shows, for each primary condition of stability, a typical temperature gradient and an illustration of the likely dispersion pattern of a cloud of small droplets.

A. Types of atmospheric stability

Neutral conditions

Normally, temperature decreases with height, referred to as the dry adiabatic lapse rate Γ. At neutral conditions, the temperature decrease with height equals the dry adiabatic lapse rate $\Gamma \approx$ -1°C/100 m. This implies that each parcel of air has the same density as its surroundings and experiences no buoyance forces, irrespective of its vertical position. This is where stability is intermediate between 'unstable' and 'stable' and may represent the best conditions for spraying. Such conditions can often occur during the early part of the morning.

Stable conditions

Under stable conditions, the temperature decrease with height is less than Γ, or $\frac{dT}{dz} > \Gamma$.
The dispersion rate of droplets may be low in stable conditions, leading to higher off-target deposition of spray at ground level because these conditions make it easier for spray to move slowly downwind (Miller *et al*., 2000 a). Under such conditions, a parcel of air is cooler and thus more dense than the surrounding air and tends to return to its original position before displacement. Wind velocities are usually low. Stable conditions can occur on dry, cloudless nights when the land cools as long wave radiation is emitted by the ground.

Unstable conditions

Under unstable conditions ($\frac{dT}{dz} < \Gamma$), a parcel of air displaced upwards from the ground will normally move into a region of lower pressure and thus expand. This expansion is normally adiabatic (i.e. there is no exchange of heat with the surrounding air) and results in the cooling of the air parcel corresponding with dry adiabatic lapse rate Γ. In summer conditions, during the late morning and afternoon, air parcels generated in this way tend to rise and remain hot and thus lighter than the surrounding air. Air made to rise under such conditions has a tendency to continue its upward motion. Usually thunderstorms develop in strongly unstable conditions. If atmospheric conditions are unstable, the dispersion of spray upwards may be high, increasing the amount of spray that enters the atmosphere.

Temperature inversion

A temperature inversion can occur when the sky is clear at night. The ground can lose heat rapidly in the atmosphere and cool layers adjacent to the ground surface are created. Air close to the ground becomes cooler than above and a temperature inversion is created which suppresses the vertical movement of air. Inversions usually form under very low wind speed conditions and spraying should be avoided since small droplets are capable of remaining airborne for long periods within the inversion layer (PISC, 2002).

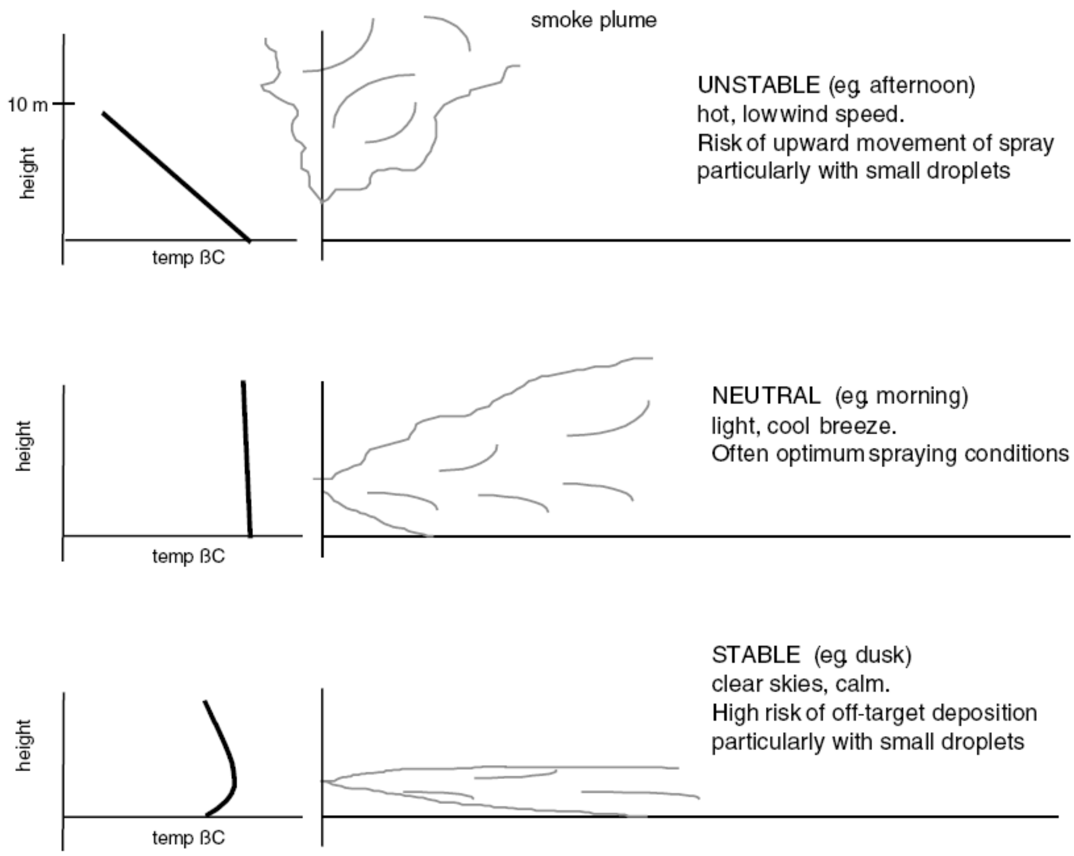

Figure 2.8 Behaviour of smoke or dust under various conditions of atmospheric stability (PISC, 2002)

B. Measures of atmospheric stability

Different measures have been used to characterise the atmospheric stability in spray drift studies (Hadfield, 1984).

Richardson number

The potential temperature θ_t of a volume dry air at pressure p and temperature T, is a convenient thermodynamic representation of the effective temperature the air would have if it was transferred adiabatically to the level with the normal pressure p_0. This potential temperature can be calculated as follows (Liljequist, 1962):

$$\theta_t = T.(\frac{p_0}{p})^{\frac{\gamma-1}{\gamma}} \qquad (2.2)$$

where

θ_t = Potential temperature (K),
T = Absolute temperature (K),
p_0 = Normal atmospheric pressure = 101325 Pa,
p = Pressure (Pa),
γ = Heat capacity ratio of the air (-).

The dimensionless Richardson number (Ri) is used to indicate atmospheric stability and the formation of turbulence (Miller, 1993):

$$Ri = \frac{g}{T} \cdot \frac{(\frac{d\theta_t}{dz})}{(\frac{du}{dz})^2} \qquad (2.3)$$

where

u = Wind speed (m.s^{-1}),
z = Height above the ground (m).

The sign of the Richardson number is controlled by the sign of the term $\frac{d\theta_t}{dz}$. A negative value depicts unstable conditions and vice versa. The Richardson number has been used by Rutherford *et al*. (1989) and Johnstone and Huntingdon (1977). However, Rutherford *et al*. (1989) reported no improvement in the correlation between measured drift and wind speed when atmospheric stability was included in the analysis.

Stability ratio

Stability ratio (*S.R.*, °C.s^2.m^{-2}) is another way to express the atmospheric stability and has the advantage of being easy to measure. Stability ratio is defined as (Yates *et al*., 1974):

$$S.R. = \frac{10.(T_{10} - T_{2.5})}{u_5^{\ 2}} \qquad (2.4)$$

where

T_x = Temperature at a height x (m) (°C),
u_5 = Wind speed at a height of 5 m (m.s^{-1}).

The relation between *S.R.* and atmospheric stability is presented in Table 2.8.

Table 2.8: Comparison of stability ratio (*S.R.*) and observed atmospheric stability (Yates *et al*., 1974)

Atmosphere	Stability Ratio
Unstable	-1.7 < *S.R.* < - 0.1
Neutral	-0.1 ≤ *S.R.* < 0.1
Stable	0.1 ≤ *S.R.* < 1.2
Very stable	1.2 ≤ *S.R.* < 4.9

C. Relation with spray drift

Miller *et al.* (2000 a) found that atmospheric stability was the major determinant of the amount of deposition in areas adjacent to treated fields. Threadgill and Smith (1975), Thistle (2000) asserted that the dispersion of pesticide droplets is influenced by this parameter. Different authors found that wind speed dominates drift in the near field and stability in the far field (Yates *et al*., 1967; Maybank *et al*., 1978; Crabbe *et al*., 1994). In these cases, the “near field” was the downwind distance where droplets large enough to settle out by gravity forces were depositing from a definitive plume. The “far field” was the longer range downwind distances where most of the large droplets were gone and the small droplets remaining in the air were depositing by diffusion.

Hence, stability plays an important role once the spray cloud is airborne. Most of these investigations were carried out for aerial sprayings. The few ground and orchard sprayer experiments generally agree with the aerial spray literature (MacCollom *et al*., 1986;

Fox *et al*., 1993 a). Bode *et al*. (1976) noted that wind speed was more important than stability in the unstable range to neutral range when drift from ground sprayers was measured.

2.2.4.4. Temperature

The temperature has an influence on movements of the air and the relative humidity of the air. An increase of the temperature normally corresponds with a decrease in relative humidity. Evaporation will proceed faster under higher temperatures (Elliott & Wilson, 1983). As temperature increases, water-based formulations and mixtures can be exposed to greater evaporation and this can lead to the formation of smaller droplets and therefore greater drift potential (PISC, 2002). Moreover, high temperatures can also be an indicator of strong atmospheric instability leading to a convective loss of spray to the atmosphere. Different authors confirmed the importance of temperature in relation to pesticide drift (Goering & Butler, 1975; Bode *et al*., 1976; Smith *et al*., 1982 b).

2.2.4.5. Humidity

The term *relative humidity* (*RH*) is used to describe the dryness of the atmosphere. It defines the ratio of the amount of water that is contained in a sample of air to that which could be contained in the same volume of air if saturated at the same temperature. Because it is a relative measure dependent upon temperature, the *RH* increases as the temperature drops and decreases with increasing temperature (PISC, 2002).
The *wet bulb depression* (ΔT_{wb}) is defined as the difference between the ambient wet and dry bulb temperatures which gives a measure of the humidity of the air (Hartley & Graham-Bryce, 1980). The dryer the atmosphere, the greater the amount of evaporative cooling and difference between the two bulb temperatures. The relationship between dry ambient temperature, relative humidity and wet bulb depression is shown in Figure 2.9.

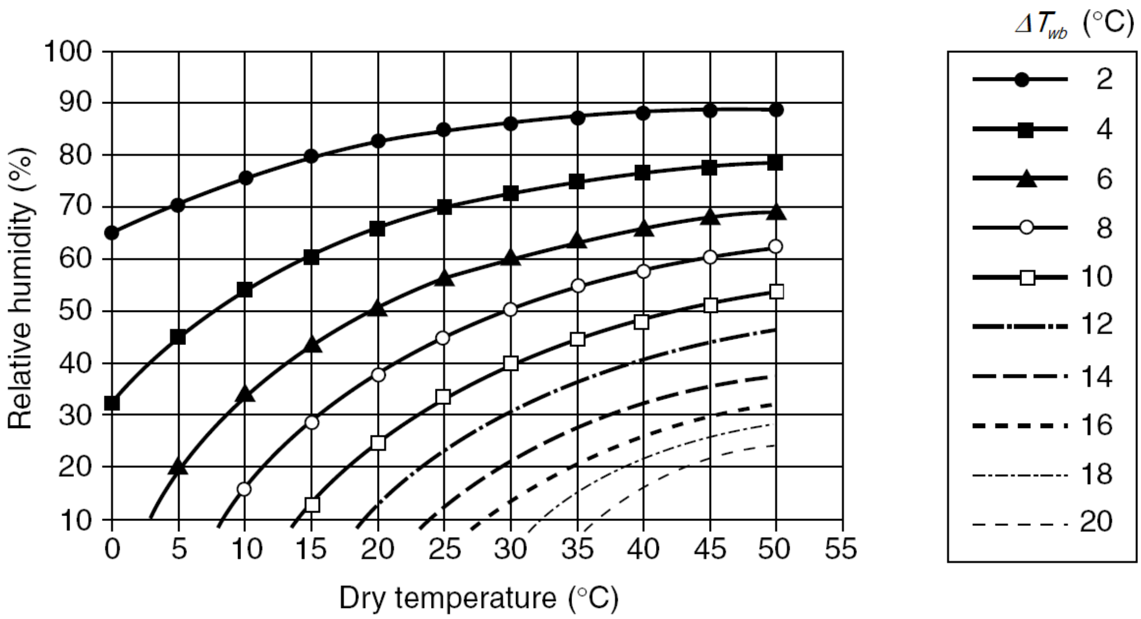

Figure 2.9: Relationship between ambient temperature, relative humidity and wet bulb depression (PISC, 2000)

The evaporation of droplets increases their drift potential by reducing their diameter. The rate of evaporation of water drops of a particular size is almost entirely dependent on the temperature of the drops and on the wet bulb depression. Theoretical studies concluded that smaller droplets evaporate faster because of different reasons (PISC, 2002).

- As the size of a droplet decreases, there is an increase in the ratio between the surface area and its volume. Consequently, a greater proportion of the volume of the droplet is exposed to the atmosphere as the droplet size decreases which accelerates its evaporation.
- As a droplet becomes smaller through evaporation, its sedimentation velocity, or rate of fall towards the ground, becomes slower. Hence a droplet remains airborne longer and is thus more susceptible to further evaporation as it becomes smaller.
- The rate of evaporation is related to the droplet size. Experiments have shown that droplets smaller than 150 µm evaporate about 27% faster than droplets above this size. This is due to a change in airflow that occurs with droplets smaller than this size. Above 150 µm, the airflow is separated from the base of a droplet and no evaporation occurs from this region. By contrast, the flow is attached everywhere on droplets less than about 150 µm and evaporation occurs from the whole surface (Spillman, 1984).

Elliott & Wilson (1983) described a simplified formula for the life time (s) of a spherical stationary water drop:

$$\text{Life time} = \frac{d^2}{80.\Delta T_{wb}} \qquad (2.5)$$

where

d = Droplet diameter (µm),

ΔT_{wb} = Wet bulb depression (°C).

Work done by Hall *et al*. (1994) and Riley *et al*. (1995) demonstrates that rate of change of droplet diameter with time is linear for freely falling water droplets. According to Asman *et al*. (2003) the evaporation and diffusion of water vapour to the surrounding air from the drop itself, as well as heat exchange between the drop and the continuous phase, are the main processes in evaporation of sprayed drops.

The relationship between drop size and relative humidity is well known (Bache & Johnstone, 1992; Miller, 1993; Kincaid & Longley, 1989) and different evaporation drop models have been developed, some of them incorporating statistical and experimental information (Ranz & Marshall, 1952; Duan *et al*. 1992, Asman *et al*., 2003). Those evaporation models have been included in computer simulations of drop trajectories assuming that drops are composed merely of water (Tsay *et al*., 2002 a; b & c).
Other models bringing into account droplet evaporation have been developed by Duan *et al*. (1992), Holterman *et al*. (1997) and Samsonov *et al*. (1998). Although the physical principles of drop evaporation in pesticide application have been well described in the bibliographic resources for several decades (Goering *et al*., 1972; Williamson & Threadgill, 1974), the rate of evaporation in agricultural spraying technology continues to be a complex problem that involves physical and chemical properties of spray liquid and drop-surrounding air conditions because of the addition of non-volatile compouds which changes the behaviour of drop evaporation (Reichard *et al*., 1992 a; Hall *et al*., 1994). Khalil *et al*. (2002) concluded that reduction in the evaporation loss may occur when adding drag-reducing polymer solutions.
The best weather conditions for spraying are mostly situated in the early morning and the early evening.

2.2.5. Drift collectors and windbreaks

2.2.5.1. Mechanisms

Artificial or vegetative drift collectors can be placed at downwind edges of fields, adjacent to susceptible areas. A vegetative barrier is usually a tree or shrub line. These drift collectors reduce spray drift by filtering the air and catching the droplets as they move in the air through or over the vegetation. They are long in the crosswind section and narrow in the along wind direction. The mechanism is illustrated in Figure 2.10.

- Assume a porous barrier immersed in a particle-laden airflow much deeper than the height of the barrier itself, so that the incident particle concentration is approximately uniform with height (point A).
- Some of the oncoming air is filtered through the barrier, while some passes over it. Particle concentrations are not changed in the air flowing over the barrier, but are strongly reduced in the through-flowing flow by deposition onto leaves and stems in the barrier (point B). There is a strong reduction in particle deposition on the surface in the immediate lee of the barrier, caused by both the reduced particle concentration and the reduced wind speed in this region. This region extends to a downwind distance of around 3 to 10 times the height of the barrier.
- Particles in the flow above the barrier are mixed downwards into the quiet zone with increasing distance from the barrier (point C). Hence, near-surface particle concentrations and surface deposition both increase, eventually recovering approximately to their values upwind of the barrier (point D). The local protection provided by a single barrier therefore effectively reduces deposition in the immediate lee of the barrier, but does not have much impact on concentrations further downwind.

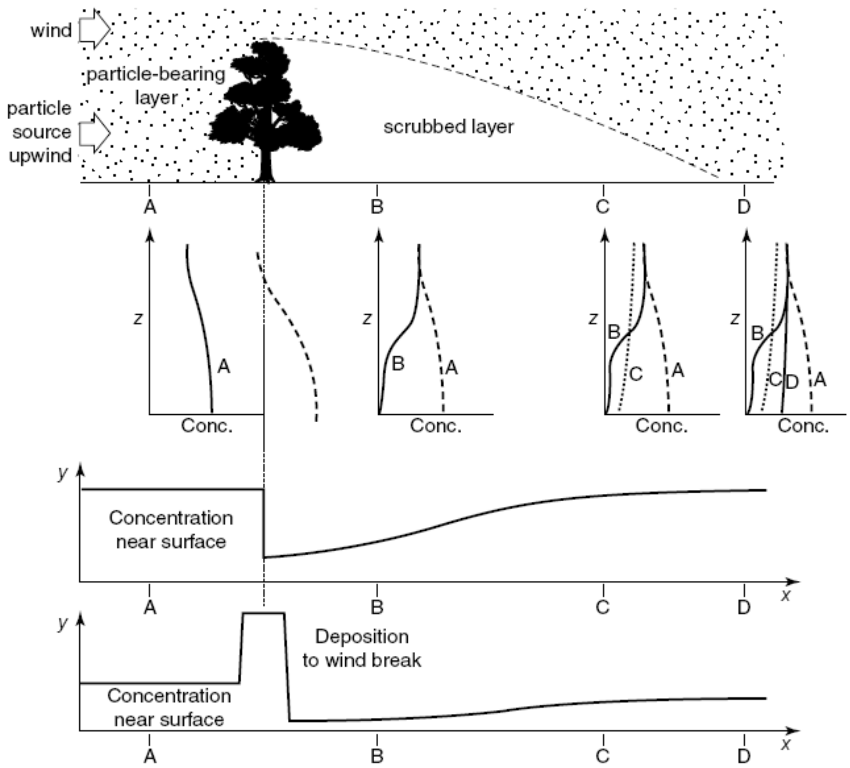

Figure 2.10: Diagram illustrating droplet deposition downwind of a spray area being affected by a porous vegetative barrier (Raupach *et al*., 2000)

2.2.5.2. Design of drift collectors

The ability of natural or artificial structures to intercept and retain droplets is determined largely by the collection efficiency of the structures and was studied among others by Raupach *et al*. (2001 b). Collection efficiency is assessed as the droplet mass fraction deposited on the surface from the bulk air volume (Parkin & Merritt, 1980; Matthews, 1992). In other words, it expresses the percentage of the spray cloud that is collected by the structure. Since most objects cause a change in airflow patterns, air is deflected by collectors, causing typically less than 100% of the spray cloud to be collected. It should also be noted that leaf structures can have a large impact on collection efficiency. Droplet size is an important parameter affecting collection efficiency. Bache (1980) demonstrated that collection efficiency is affected mainly by the design of the drift collector and the droplet sizes. Wind speed is less important.

Plant surfaces that present a small frontal area to the moving droplets are the most successful at catching droplets. Trees that have a thin needle-like foliage and numerous smack branches are particularly suitable. Large leaves that are covered in small hairs can also be very efficient at removing droplets. Most natural surfaces are not smooth. Plants may have a complex rough surface comprising small protruding spikes or hairs and leaf veins. All these factors help to increase the catch efficiency of the plant. Movement of the leaves caused by the flow of air around shrubs and trees also increases the catch efficiency.

In designing a vegetative buffer element, the primary aim is to maximize the catching surface for the spray droplets whilst at the same time, minimizing the amount of airflow deviation around the structure. This requirement to minimize the airflow deviation may be in contrast to trees used for windbreaks, where the aim is to direct the air away from the downwind side of the buffer. A breeze passing through a vegetative barrier will tend to enhance conditions for capture (PISC, 2002).

If a dense barrier is presented to an airflow, air tends to flow up and over the barriers (Spillman & Woods, 1989). This is illustrated in Figure 2.11 (left) where the airflow deviation over a solid board (0% porosity) placed in a wind tunnel is shown. The region directly behind the barrier is characterised by low pressure and turbulent eddies.

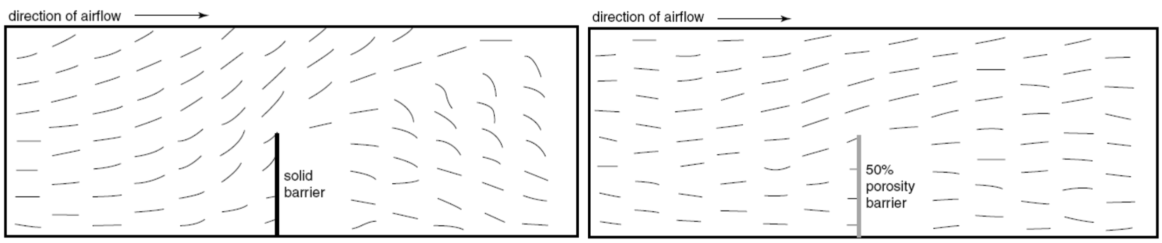

Figure 2.11: Effect of collector porosity on airflow characteristics (PISC, 2002)

During spray application, it is the small droplets that are most prone to drift. Because small droplets move readily along in an air stream, they can also be easily carried by an air stream in, above and around buffer vegetation. When air is deflected above a low porosity tree line, small droplets are also carried over the top of the barrier. Dense, low porosity structures are less effective in trapping spray drift except in the immediate region behind the barrier (PISC, 2002).

A porous barrier, however, allows some air to pass through its structure while still deflecting some airflow over the top. This is illustrated in Figure 2.11 (right) where a wire mesh with 50% porosity is used. The figure shows that there is less deviation of air over the top of the barrier compared to the solid barrier. The airflow behind the barrier was also straighter and less turbulent than behind the solid barrier. With a porous barrier, droplets can be carried through a buffer and this increases the chance of capture within the structure. A porous barrier can effect a greater removal of spray droplets than the solid barrier (PISC, 2002).

As a general guide, the minimum height of the buffer should be double the release height. However, protection from spray drift is only in the region 3-10 collector heights downwind. The closer the collector is to the release point, the greater the proportion of spray that will be intercepted (PISC, 2002).

2.2.5.3. Drift reduction benefits

Following release from a sprayer, droplets will tend to travel with their initial trajectory and velocity, and then be carried by the ambient wind until deposition. If vegetation or other structures are in the path of the spray, droplets may be intercepted and thereby not tend to drift as far. Different studies (Holland *et al*., 1997; Praat *et al*, 2000) have shown that in orchard spraying, canopy development and sprayer position relative to the canopy can have a major influence on spray drift. Praat *et al*. (2000) measured 25 times less drift from a fully foliated canopy compared with a dormant canopy.

In The Netherlands, it was noted that a windbreak on the outer edge of a field can reduce spray drift by 70 to 90% in the zone 0-3 m downwind of the windbreak (Porskamp *et al*., 1994; van de Zande *et al*., 2000 b). Many studies have been made in The Netherlands to support such interests (Heijne, 2000). Porskamp *et al.* (1994) observed an 85% reduction in drift from using an alder windbreak downwind of fields being sprayed. The research involved a series of orchard sprayings at different times of the year. Reductions were greater in summer and early fall (at least 90% reduction in drift when a hedge was present) than in April (68-79% reduction in drift with the hedge). It was concluded that reductions in drift of 68% to >90% could be obtained using a windbreak around an orchard being sprayed. The range reflects differences in leaf density of the windbreaks and the wind speeds during the studies. Fewer studies have been conducted in The Netherlands to investigate the effect of windbreak height on drift for field sprayings. Van de Zande *et al*. (2000 a) concluded that deposition drift decreased with greater ratio of windbreak to crop height based on a series of measurements with Elephant grass (*Miscanthus*), located at 1 m from the edge of the crop and heights of 0.5, 1.0 and 1.5 m.

The above studies showed that vegetation can significantly reduce drift from spray applications to orchards and row crops. Other studies have shown that artificial materials can also be used to intercept drift and thereby reduce deposition rates in the field. Artificial netting provided a 68-88% reduction in drift in studies conducted with ornamental spraying by Smidt *et al*. (1998), and 45-80% reduction in drift from fruit orchard spraying (Heijne *et al*, 1999). Davis *et al*. (1993) concluded that drift reductions using hedges were not effective when wind speeds were greater than 3 $m.s^{-1}$, but were reasonably effective at lower wind speeds.

Miller *et al*. (2000 b) studied the effect of vegetative buffers on reducing drift. They found that tall grass was 30% more effective than a cut grass/flower mixture at reducing drift. Their field results agreed with previous wind tunnel testing (Miller & Lane, 1999) supporting the concept that establishing a field margin with some tall vegetation gives the potential to reduce the risk of drift beyond a sprayed field. They noted that the vegetation acts as a filter for airborne droplets and impedes airflow. They added that very dense vegetation will not allow adequate airflow through the canopy and the main flow could be above the filter strip such that the filtering effect is substantially reduced and the overall effect on drift dispersal is negative.

Dorr *et al*. (1998) studied drift reductions from vegetated buffer zones. They found that spray drift could be reduced by approximately 50% using a row of trees downwind of the spray application area. The porosity of the vegetation was only 10 to 20%, and more effective drift reduction was inferred for canopies with higher porosity of around 40 to 50%.

In conclusion, reductions in drift by the use of natural and artificial barriers depend on the structure and location of the barrier, as well as the wind speed and droplet size spectrum of the spray. There is general agreement in the literature that a drift reduction of 45 to 90% can be achieved through appropriate barriers (Hewitt, 2001) which is supported by measuring results from Richardson *et al*. (2002; 2004).

2.2.6. Crop characteristics

Taylor *et al*. (1999) indicate that a boom sprayer operating over a tall grass surface gave levels of drift that were in the range of 138 to 270% of those for an equivalent sprayer operating over a short grass surface. Van de Zande *et al*. (2006) assessed the effect of crop type on spray drift by spraying potatoes, cereals, sugar beet, flower bulbs, maize and a bare sole surface with a standard XR 110 04 flat fan nozzle and a pre-orifice DG 110 04 flat fan nozzle at 3 bar pressure. They found that spray drift deposition is highest for potato spraying, followed by maize, flower bulb, bare soil, sugar beet and cereals. The trend for spray drift deposition with crop types is similar for both the standard flat fan nozzle and the pre-orifice flat fan nozzle. Ganzelmeier *et al*. (1995) found only minor differences in spray drift when spraying a cereal crop and a bare soil. Therefore only one set of drift values was proposed for field crops.

2.2.7. Buffer zones or no-spray zones

Nature is in decline in many countries with nature in arable regions being no exception. Various factors are responsible for the decline and some of them are related to the intensification of agricultural operations. One of the most significant factors in arable farming is pesticide use. Different researchers concluded that the nature conservation value of arable land can be substantially enhanced by reducing pesticide use along field margins, as this leads to a marked increase in the abundance of wild flowers, insects and birds in the unsprayed crop edges (Rands, 1985; Rands & Sotherton, 1986; Muscutt *et al*., 1993; Boatman, 1994).

On the other side, it is recognised that plant protection products are economically important in agriculture and should be made available to farmers and growers provided that they do not present risks. A possible strategy is to prohibit the treatment of crops within a boundary adjacent to surface water. Such buffer zones or no-spray zones are a way of protecting organisms or places from the effects of spray drift by imposing a spatial separation between the place of spray application and organisms or areas that need to be protected (Robinson *et al*., 2000). These buffer zones can be defined as follows (Australian Pesticides & Veterinary Medicines Authority, 2005):

> "A buffer zone is an area in which direct application of the agricultural chemical is prohibited; this area is specified in distance between the closest point of direct chemical application and the nearest boundary of a site to be protected."

For individual chemicals where the predicted environmental concentration (*PEC*) is known, it is possible to determine the required buffer distance from a sensitive target. The buffer distance required is the point at which the *PEC* becomes less than the no effect concentration (*NEC*) (De Schampheleire *et al.*, 2006 b). This buffer distance will depend upon factors such as the weather conditions, the application method and the toxicity of the chemical to the sensitive species concerned. This approach is followed by many authors for different organisms like aquatic animals (Payne *et al.*, 1988; Ernst *et al.*, 1991; Helson *et al.*, 1993; Lahr *et al.*, 2000), honeybees (Davis & Williams, 1990; Çilgi & Jepson, 1995) and butterflies and plants (Marrs *et al.*, 1993). They all combined downwind profiles of pesticide deposition with results from in situ bioassays and/or laboratory toxicity tests with sensitive species. Dabrowski *et al.* (2005) investigated the potential of an aquatic vegetation for the interception of spray drift. Pesticide deposition was reduced by up to 67% in the studied stream.

A number of types of buffer zone are already used in modern agriculture as a part of catchment strategy for the protection of surface water from nitrate, phosphate and sediment incursion. Recommended or mandatory buffer distances are increasingly being incorporated into product labels in many countries like Belgium, The Netherlands, United Kingdom, Germany, etc. (§ 2.5). Although, it is recognised that buffer zones can provide opportunities which are likely to be of environmental benefit, their use imposes considerable practical and economic penalties, especially in areas with small fields and many ditches (Cook, 1997). On the other side, crop edges are mostly of less economic value than field interiors and their management often requires additional effort (Boatman & Sotherton, 1988).

De Snoo and de Wit (1998) measured drift adjacent to the sprayed field on the ditch bank and in the ditch. They concluded that 8 of the 17 tested pesticides posed a risk to aquatic organisms. Creation of a 3 m buffer zone decreased drift deposition in the ditch by a minimum of 95% and enhanced biodiversity in farming regions. Adjacent to the buffer zone, only 4 of the 17 pesticides investigated posed a (minor) risk. Porskamp *et al.* (1994) measured a reduction of the deposition on surface water of 70% by means of a 2.25 m non-cropped and non-sprayed zone in potatoes. Marrs and Frost (1997) suggested that a bufferzone of 8 m would in general be adequate to protect sensitive habitats. A cost-benefit analysis carried out by de Snoo (1999) based on the yield losses showed that it is very feasible to incorporate unsprayed crop edges in the cultivation of winter wheat and potatoes. In sugar beet, however, the cost is too high. However, for reasons to do with agronomy, farming equipment and socio-psychology, farmers will accept unsprayed cereal edges or grass strips but not unsprayed potato edges. From their perspective the most important aspect for acceptance in farming practice is a flexible width of the unsprayed crop edges.

Miller *et al.* (2000 b) emphasized the importance of the plant structure in the buffer zone to reduce the risk of drift onto adjoining surface water and to maintain high biodiversity.

2.3. Drift experiments

2.3.1. Spray drift sampling and tracing techniques

2.3.1.1. Requirements for drift measurements

A major requirement for the measurement of spray drift is to capture and quantify a volume of spray liquid in small droplets passing through a defined frame at a given distance downwind of the spray generation system. Measures of drift can relate to either the deposition of spray onto horizontal surfaces outside of the treatment area or to airborne spray profiles that can be characterised at given distances downwind of the treatment area. Deposition onto horizontal surfaces is relevant to the assessment of the risk of contamination of, for example, surface water; whereas the measurement of airborne profiles is relevant to risk assessments relating to inhalation effects and to the contamination of, for example, vegetative structures at field boundaries. For these purposes, different types of samplers and tracers can be used.
In the International Standard ISO 22866 (2005) some important general specifications on the selection and handling of spray drift collectors are given.

- The recovery and stability of the tracer on the target collector or sampler shall be verified prior to the start of any spray drift measurement.
- Procedures for handling collectors or samplers prior to and post exposure to spray drift shall be established that minimize any risk of cross-contamination. The potential for cross-contamination and tracer degradation shall be monitored during a trial using clean collectors or samplers and those loaded with a measured volume of the tracer solution.
- After use, collectors or samplers should be stored for the minimum period possible. Where storage is necessary, this should be in conditions appropriate to the tracer, typically dry, in darkness, and at a temperature of less than 4°C, with any risk of condensation minimized (since this may result in inaccuracy).
- Deposits on collectors or samplers should be calculated based on the calibration of the tracing technique with samples of the spray liquid taken from a nozzle at the time of the spraying.

2.3.1.2. Drift collectors and samplers

A. Passive collectors

An overview of passive collectors that have already been used in previous researches are listed in Table 2.9.

Table 2.9: Overview of the most important passive collectors found in literature

Collection surface	Characteristics	Comments	References
Cotton line	Very high collection efficiency, variable and uncertain collection area	Determine mean sampling dimension, used to sample airborne drift	Bui *et al.* (1998)
Filter Cloth	Very high collection efficiency, variable and uncertain collection area	Determine mean sampling dimension, used to sample airborne drift	de Jong *et al.* (2000), Heijne *et al.* (2002), Brusselman *et al.* (2005), De Schampheleire *et al.* (2006 c)
Metal cylinders	High collection efficiency, known sampling area	Verification of tracer retention and recovery necessary, used to sample airborne drift	Davis *et al.* (1993)

Collection surface	Characteristics	Comments	References
Plastic rods	Known collection area, Easy to handle, reasonable collection efficiency, diameter = 3 mm		Norby and Skuterud (1974)
Microscope slide	Low collector efficiency when sampling airborne drift	Used to determine sedimenting drift, mounted horizontally	Byass and Lake (1977)
Nylon screen			Derksen *et al*. (1999), Fox *et al*. (2004)
(Filter) Paper surfaces	Low collector efficiency when sampling airborne drift	Used to determine sedimenting drift, mounted horizontally	Norby and Skuterud, (1974), Johnstone and Huntingdon (1977), Bui *et al*. (1998), Mathers *et al*. (2000), Brusselman *et al*. (2005), Nuyttens *et al.* (2007 a)
Petri dishes	Low collector efficiency when sampling airborne drift	Used to determine sedimenting drift, mounted horizontally	Wolf *et al*. (2004), Caldwell & Wolf (2006)
Pipe cleaners	Very high collection efficiency, variable and uncertain collection area	Determine mean sampling dimension, used to sample airborne drift	Miller *et al*. (1989 b), May (1991), Nordbo and Taylor (1991), Taylor and Andersen (1991), Davis *et al*. (1993)
Polyester film targets			Smith *et al*. (1982 b)
Polythene line	High collection efficiency, good recovery characteristics, known sampling area, diameter = 1.98-3.0 mm	Verification of tracer retention and recovery necessary, used to sample airborne drift	Lake *et al*. (1978), Sharp (1984), Lloyd *et al*. (1986), Gilbert and Bell (1988), Miller *et al*. (1989 b), Walklate (1992), Miller and Smith (1997), Murphy *et al*. (2000), Mathers *et al*., 2000
Scouring pads ("Pan cleaners")	Very high collection efficiency, variable and uncertain collection area	Determine mean sampling dimension, used to sample airborne drift, Pads made to standardised weight and used in German standard	de Jong *et al*. (2000)
Test tube brush			Cross (1991 b), Davis *et al*. (1993)
Woollen line	Very high collection efficiency, variable and uncertain collection area	Determine mean sampling dimension, used to sample airborne drift	Western and Hislop (1991)
Hair curler	High collection efficiency, easy to handle, unknown aerodynamic characteristics		Parkin and Merritt (1988), Miller *et al*. (1989 b), Davis *et al*. (1993)
Plant species		The effect of toxic vapours produced by some herbicides may be from the effects of the droplet drift.	Weisser *et al*. (2002)
Plastic sheets/lids			Fox *et al*. (1993 b), Carlsen *et al*. (2006 a; b)

Passive collectors have been used for sedimenting as well as for airborne spray drift measurements with tracers, such as pipe cleaners, filter paper and different diameter polymer lines, with diverse collection efficiency (Table 2.9). Spray droplets are collected on static targets by the process of impaction and care is needed to select a target that will collect a representative sample of a drifting spray. Collection efficiency is a function of target shape, a characteristic dimension, local wind speed and the size of the droplets to be captured (May & Clifford, 1967). Collection efficiency can be considered as the ratio of actual collected tracer to the total amount of tracer that is in the air and theoretically collectable by the sampler. Wide surfaces can collect significant volumes of spray but their collection efficiency is low due to inertial separation and is influenced by drop size. Narrow surfaces sample sprays efficiently but they collect only a small volume of the spray. Thus a compromise has to be made. Matrix samplers (Miller, 1993), which consist of arrays of narrow fibres are designed to increase sample area whilst retaining sampling efficiency.

Many measurements of drift are comparative and in such cases it may not be necessary to define in detail the sampling volume of the collector provided that it is the same for all spraying treatments being compared. This may be difficult to achieve since many passive collectors have a sampling volume and collection efficiency that is a function of both droplet size and local wind speed conditions (May & Clifford, 1967). Spraying systems that are likely to give differences in downwind drift may also have different drift droplet sizes and/or airborne drift profiles and it is important that the characteristics of the drift collector do not mask the relative drift magnitudes.

In other cases, an estimate of the absolute quantity of drifting spray is required. For example. in risk assessment work and in comparisons made between different systems in different conditions. In these situations it is necessary to be able to estimate the sampling volume and collection efficiency of the drift measurement technique and to relate the captured drift to the output from the spraying system. Miller *et al*. (1989 b) reported that collection efficiencies will commonly be in the order of 50% or less. Recently, collection efficiency of drift collectors has been studied by means of Computational Fluid Dynamics simulations (Parkin & Young, 2000).

Passive airborne spray drift collectors

Herbst and Molnar (2002) analysed different drift collectors for airborne drift in a wind tunnel. They concluded that cylindrical collectors with a diameter of 2 mm and characterized by a smooth and well-defined surface were the most suitable collectors for airborne drift. For volatile fluids such as water, the evaporation rate can be an important disadvantage and hinder the sampling of airborne spray drift away from downwind distances (Solanelles *et al*., 1996). Indeed, Walklate (1992) indicated problems in the collection efficiency due to the change in diameter of drops. Fox *et al*. (2004) assessed spray collection efficiency of nylon screens, and found that screens with a porosity of about 56% were the most effective. They collected about 50-70% of spray droplets released in wind tunnel evaluations. Other supposedly efficient passive airborne collectors that have been used include pipe cleaners, scouring pads, test tube brushes, woollen lines and hair curlers as described in Table 2.9.

The collection of drops onto cylindrical volumes is influenced by the relative sizes of the fibre and drop (interception), the collision of drops with fibres due to the deviation of streamlines (inertial impaction) and the retention of drops on the fibre surface (adhesion). Experiments have indicated that the collection of drops onto cylinders can be described by a single sigmoidal curve when collection efficiency is plotted against Stokes number (*St*)

(May & Clifford, 1967). For the impaction of drops on cylinders in an airstream, Stokes number is defined by:

$$St = \frac{u.d^2}{18.\upsilon_a.D_l} \qquad (2.6)$$

Where u is the windspeed (m.s^{-1}), d is droplet diameter (m), D_l line diameter (m) and υ_a kinematic viscosity of air (m².s^{-1}). At high values of the Stokes number (St > 100), 100% collection efficiency is predicted. In practice, a maximum efficiency of 100% will not be reached and decreases with increasing line diameter (Parkin & Young, 2000).

Passive sedimenting spray drift collectors

Collection by *horizontal fallout sheets* is a complex combination of sedimentation and inertial impaction of drops that are large enough to settle downwards. Thus, fallout sheets are used for the measurement of sedimenting spray drift (Yates *et al.*, 1978; Brusselman *et al.*, 2005; Nuyttens *et al.*, 2007 a) and they are found to be a good and reliable method for collection of spray drift (Carlsen *et al.*, 2006 a).

B. Dynamic samplers

Dynamic air-sampling methods to determine gas-particle distribution were studied by several authors (Bui *et al.*, 1998; Amin *et al.*, 1999; Sanusi *et al.*, 1999), as well as different partitioning models (Lohmann *et al.*, 2000). These studies demonstrated the complexity of the measurement of the partition gas-particle, due to the influence of the environmental conditions. Moreover, much information is still necessary on physical and chemical properties of the pesticides. An overview of different dynamic sampling methods used in previous researches are listed in Table 2.10.

Table 2.10: Overview of the most important dynamic samplers found in literature

Sampler	Characteristics	Comments	References
Cascade impactor	Also give a coarse classification of the droplet size distribution		Grover *et al*. (1978), Parkin and Merritt (1988)
Suction sampler or Volumetric air sampler	Active sampler, high collection efficiency	Used to sample airborne drift only, collection area difficult to define unless sampling is isokinetic	Yates *et al*. (1976), Grover *et al*. (1978), Gilbert and Bell (1988), Zabik and Seiber (1993), Wolf *et al*. (1993), Salyani and Cromwell (1993), Fox *et al*. (1993 b), Bui *et al*. (1998)
“Rotorods” or Rotory sampler	Active sampler, high collection efficiency except for particles smaller than 7 µm, simplicity in design and operation	Used to sample airborne drift only, collection area difficult to define unless sampling is isokinetic, small collection surfaces can readily become overloaded	Hadfield (1984), Parkin and Merritt (1988), Miller *et al*. (1989 b), Bui *et al*. (1998)

Volumetric air sampling and cascade impactors

Many field measurements of spray drift have been based on determinations of the airborne concentrations of spray droplets at defined positions downwind of the spray release by using *volumetric air samplers*. Air is drawn over a filtering medium at a known controlled rate and the quantity of spray captured determined analytically. The idealized conditions for representative sampling with this type of device are (Hadfield, 1984) (Figure 2.12):

1. That the axis of the sampling probe is parallel to the direction of the airflow during the sampling period (isoaxiallity). If this condition is not met (Figure 2.12 c), then the larger droplets entering a sampling tube are more likely to impact on the side of the tube because of their momentum and this will bias the sample reaching the filter medium.
2. That the mean flow velocity in the sampling probe is equal to the velocity of the air stream (isokinesis). If this condition is not met (Figure 2.12 b), the particle size distribution in the sampled air will again be distorted because of the effects of momentum of the larger particles at the entry to the sampling probe.
3. The walls of the sampling probe should be thin so as to minimize the probability of droplet impaction and shatter onto the sampling filter.

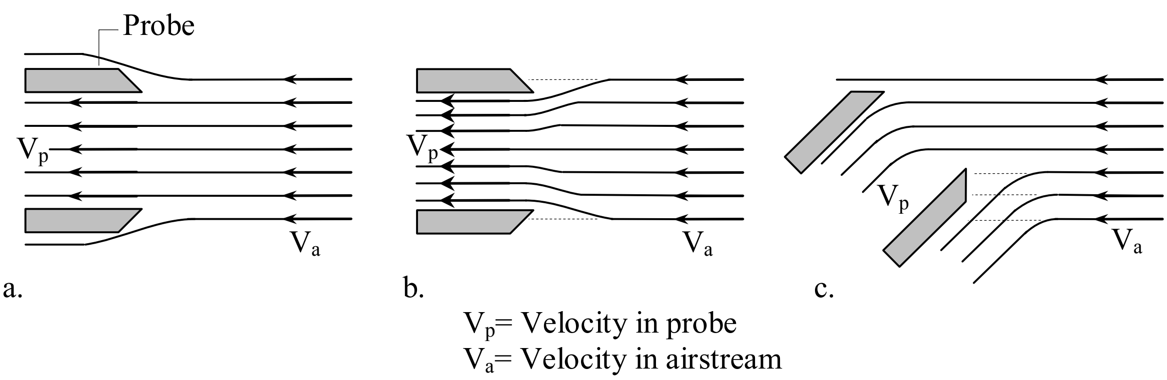

Figure 2.12: Volumetric air sampling arrangements. (a) Isokinetic sampling (b) Sampling not-isokinetic (c) Sampling not isoaxial

Conditions 1 and 3 above are readily achievable for spray drift sampling. The probe can be pointed into the airstream using a wind vane and the probe entry made as a knife edge to minimize the disturbance to the airflow. Because of the variations in natural wind speed, true isokinetic sampling of spray drift is impractical and devices should therefore be designed to sample in a manner approximating to isokinesis (Wight, 1994). Recently, Thomson and Smith (2000) developed an isokinetical sampling system which is stable through all speed ranges.

Grover *et al*. (1978) used 175 mm diameter filter papers with a constant airflow rate through the sample of 10 $L.min^{-1}$ maintained by a metering orifice. Sampling at a fixed air volume flow rate rather than an approximation to isokinesis will give sampling errors but these will be less important in a comparative test protocol (Gilbert & Bell, 1988). Aspirated air samplers at 1.5 m above the ground and at 8 m and 50 m downwind from the spray track have been used by Gilbert and Bell (1988) to provide an estimate of the risk of bystander inhalation of spray drift. Different other researchers also used volumetric air samplers like Yates *et al*. (1976), Zabik and Seiber (1993), Wolf *et al*. (1993), Salyani and

Cromwell (1993) and Fox *et al*. (1993 b). When using these devices, it is essential that users adhere to proper calibration, control and use procedures. Bui *et al*. (1998) indicated that volumetric air sampling techniques collected more drift of malathion than different other passive collectors and Rotorod samplers.

A *cascade impactor* consists of an aspirated air sampler with a series of collecting stages arranged such that at each successive stage, smaller droplet sizes are collected (Parkin and Merritt, 1988). At each stage the flow is directed towards a collection surface such as a glass slide at a velocity that increases in successive stages so that smaller droplets are collected as the air sample passes through the collector. Cascade impactors, therefore, give a coarse classification of the droplet size distribution of the drifting spray. Four-stage cascade impactors sampling at a constant rate of 17.5 L.min^{-1} at downwind distances of 5 and 60 m were used by Grover *et al*. (1978) to characterize the drift from boom sprayers. They measured volume median diameters in the drifting spray cloud of 18-21 μm.

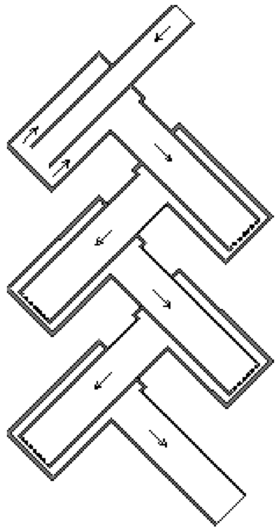

Figure 2.13: Marple-Miller five stage cascade impactor

Possible disadvantages of volumetric air samplers and cascade impactors, other than the errors associated with non-isokinetic sampling, are the high cost of the samplers, their complexity and the large power requirement to draw high air volume rates through fine filtering media. These disadvantages may be particularly limiting when the objective is to obtain representative measures of the total drift from sprayers operating in field conditions. Advantages of these systems mainly relate to the high collection efficiencies of small droplets. Cascade impactors provide an estimate of the drifting droplet size and when used with wet collection surfaces can be used to quantify the drift of sprays containing living organisms such as viruses and bacteria.

Rotary samplers

High droplet collection efficiencies can also be achieved by rotating collection surfaces about a vertical central axis. This is the principle of the Rotary sampler (Hadfield, 1984; Parkin & Merritt, 1988). An original version of the system used 'H' or 'U' shaped rotors 80 mm in diameter and 120 mm tall rotating at a controlled speed of 2400 rev.min^{-1} with 0.4 and 1.5 mm collecting surfaces on the vertical arms. Parkin and Merritt (1988) reported that this arrangement had capture efficiencies of up to 85% with 10 μm droplets.

Other configurations of the system have been used with different dimensions for the rotor and collection surfaces (Hadfield, 1984; Miller *et al*., 1989 b).

This type of sampler measures mean airborne concentrations over a given exposure time. With small collecting surfaces, high collection efficiencies and high volumetric sampling rates (Hadfield, 1984), the collector can saturate if used to sample spray drift close to a machine in laboratory or field conditions. The use of larger collection surfaces such as microscope slides can increase the total collection capacity but will usually not increase the time to saturation. However, a major problem with rotary samplers is the airflow generated by the rotation of the collection surfaces (Elliott & Wilson, 1983; Miller *et al*., 1989 b) which alters the sampling volume and which is increased by using larger collection surfaces. When sampling sprays with large droplets there are possible inaccuracies due to droplet shatter or impact with the collector surface but such errors are not usually important in drift sampling.

Rotary samplers are convenient for field use because they can be powered from battery packs and controlled to operate at a pre-set speed. Such units have therefore been used by a number of workers including Grover *et al*. (1978) and Cooke *et al*. (1990).

2.3.1.3. Tracers

Although tracer methods have been shown to have a number of practical limitations, most of these can be circumvented by thoughtful selection of tracers and attention to experimental procedures and analytical techniques. A good tracer should be easily and completely recovered from both artificial and natural targets. The recovery rate may be defined as the ratio of the measured tracer deposit to the amount of tracer applied. It may be affected by dye degradation (e.g. due to exposure to sunlight), background deposits (substances with properties similar to the tracer's that are already present on the target, e.g. pesticide residues or natural dyes emitted by the leaves) and the extraction process. Different tracer types have been used for pesticide spray drift assessment in order to simulate the deposition of pesticides, in many cases in combination with a non-ionic surfactant. In practice, tracers comprise four groups, namely fluorescent tracer dyes, visible dyes, real pesticides and metal ions, and have been reviewed by Cooke and Hislop (1993).

A. Fluorescent tracer dyes

Fluorescent tracer dyes have been widely used for spray deposit assessment from agricultural sprayers because of the relatively easy and inexpensive procedure involved, their high sensitivity and to avoid exposure of both the environment and people to pesticides (Fox *et al*, 1990; 1993 a). Fluorescein (Holownicki *et al*., 1995; Kaul *et al*., 1996 a), Rhodamine (Richardson *et al*., 1989; Brown & Sidahmed, 2001), Brilliant Sulfaflavine (Bäcker & Rühling, 1991; Pergher & Gubiani, 1995), Brilliant Sulfoflavine (Smith *et al*., 2000 a; Heijne *et al*., 2002), BASO Red (Salyani & Cromwell, 1992), Helios (Raisigl *et al*., 1991) and Tinopal (Furness, 1991; Fox *et al*., 1993 a) are reported, among others. A complete list of fluorescent tracers and references is presented in Table 2.13. All of them are analysed by means of fluorescent spectrometry.

Table 2.11: Overview of different fluorescent tracers found in literature

Product	Manufacturer	Colour	References	Remarks
Baso Red			Salyani and Cromwell, (1993), Pergher (2001)	
Brilliant sulfaflavine			Bäcker and Rühling (1991), Pergher and Gubiani (1995), Downer *et al*. (1997)	
Brilliant sulfoflavine (BSF)	Chroma	yellow	Bau *et al*. (1971), Bode *et al*. (1976), Smith *et al*. (1982 b), Sanderson *et al*. (1993), Cai and Stark (1997), van de Zande *et al*. (2000 b), de Jong *et al*. (2000), Smith *et al*. (2000 a), Heijne *et al*. (2002), Nuyttens *et al*. (2007 a)	Limited photodegradation, *: 2-3 $g.L^{-1}$ **: 0.0005-0.005 $\mu g.cm^{-2}$
Caracid Brilliant Flavine	Carolina Color and Chemical Co.		Bouse *et al*. (1994)	
Eosine	Chroma	red	Cai and Stark (1997), Downer *et al*. (1997)	Photodegradation
Fluorescein	Sigma-Aldrich		Western *et al*. (1989), Davis *et al*. (1992), Holownicki *et al*. (1995), Kaul *et al*. (1996 a), Cai and Stark (1997), Longley *et al*. (1997), Longley and Sotherton (1997)	Photodegradation
Helios			Raisigl *et al*. (1991), Heijne *et al*. (2002)	
Pyranine	Bayer	yellow-green	Herbst (2006)	Photodegradation, *: 300 $g.L^{-1}$ **: 2×10^{-9} $g.L^{-1}$
Renaissance W15			Brusselman *et al*. (2005)	
Rhodamine	Chroma	yellow-brown	Bode *et al*. (1976), Ford (1986), Richardson *et al*. (1989), Sanderson *et al*. (1993), Wolf *et al*. (1993), Cai and Stark (1997), Cross *et al*. (1997), Downer *et al*. (1997), Derksen *et al*. (1999), Brown and Sidahmed (2001), Caldwell and Wolf (2006)	Photodegradation
Tinopal	Ciba	white	Furness (1991), Fox *et al*. (1993 a), Downer *et al*., (1997), Cai and Stark (1997)	Photodegradation
Uvitex	Ciba	violet-blue		Solvent required *: 500 $g.L^{-1}$
Uvitex OB	Ciba	yellow-orange	Downer *et al*. (1997), Parkin and Young (2000)	Solvent + appropriate formulation required *: 600 $g.L^{-1}$ **: 1×10^{-6} $g.L^{-1}$
Uranin (sodium fluorescein)	BASF	orange	Ford (1986), Miller *et al*. (1989 b), Davis *et al*. (1993), Parkin and Wheeler (1996), Cross *et al*. (1997)	Photodegradation *: 600 $g.L^{-1}$

*: solubility; **: detection limit

However, most fluorescent dyes are photosensitive and degrade when exposed to solar radiation (Sharp, 1974; Goering & Butler, 1974; Yates *et al*., 1976; Salyani, 1993; Cross *et al*., 1997; Cai & Stark, 1997). Being aware of the dye degradation, Bode *et al*. (1976) collected their drift targets immediately after spraying. Pergher and Gubiani (1995) performed their experiments in the evening, with solar radiation lower than 70 $W.m^{-2}$. Others have made tests to quantify the degradation rate under different sampling techniques (Salyani & Cromwell, 1992; Brusselman *et al*., 2005). According to the tracer dye and sampling technique, the degradation rate can vary and hinder a correct measurement. Hence, it is important to verify the recovery and stability of the tracer on the target collector prior to the start of a drift experiment (ISO 22866, 2005). Cai and Stark (1997) compared the performance of five different fluorescent dyes and selected Brilliant Sulfoflavine as the best tracer to reproduce the atmospheric transport of pesticides, since its degradation is only 11% after 8 h exposure to sunlight. Droplet size spectra measurements with and without the fluorescent dyes Rhodamine and Brilliant Sulfaflavine showed that fluorescent dyes do not significantly affect the droplet spectra (Hewitt *et al*., 1994).

Another problem is the fact that fluorescent tracer dyes are potentially susceptible to irreversible adsorption to plant tissue. Reports about the use of fluorescent tracer dyes in multiple tracer studies are sparse. Goering and Butler (1975) and Cai and Stark (1997) described the use of twin fluorescent tracers to study spray drift. Using only two components, they were able to select tracers with widely differing absorption wavelengths and emission wavelengths. Cross *et al*. (1997) did the same with three fluorescent tracers, but this was only possible when relative concentrations did not exceed a ratio of 10:1.
Finally, Downer *et al*. (1997) measured important differences in droplet size distribution using different fluorescent tracer dyes compared to water mixtures. They suggest to pay attention to the droplet spectra produced by tracer solutions and to match them to the droplet spectra produced by the pesticide spray solutions they have to emulate. When comparing spray application equipment, the same tracer should be used for all the test equipment.

B. Visible dyes

Colorimetry techniques may represent an alternative to fluorometry. Lissamine Green (Cross, 1991 a), Tartrazine (Richardson *et al*., 1989; Pergher *et al*., 1997), and Erythrosine (Cross *et al*., 1997) have been used as tracer dyes. Johnstone (1977) described a twin tracer technique for measuring deposits on cotton using two oil-soluble visible dyes with different absorption characteristics that could be quantified independently in a single extract. A similar method was used by Parkin *et al*. (1985) to measure the deposition of Erythrosine and Water Bleu applied simultaneously to barley. Gilbert and Bell (1988) used Lissamine Green and Orange G to compare the contamination of bystanders arising from outdoor spray applications.

Cross *et al*. (1997) demonstrated the feasibility of combining three visible dyes to measure spray deposits on apple trees i.e. tartrazine, erythrosine and Green S. Because of the relatively broad absorbance bands of visible dyes, problems may arise when relative concentrations exceed a ratio of 20:1. Moreover, little information is available on their (photo)stability under field and laboratory conditions and in general the recovery is poor. An overview of different visible dyes used as tracers is given in Table 2.12. Visible dyes are analysed using photometry.

Table 2.12: Overview of different visible dyes used as tracers found in literature

Product	Manufacturer	Colour	References	Remarks
Blue patent (E131)		blue	Pergher (2001)	*: 50 $g.L^{-1}$ **: 2×10^{-7} $g.L^{-1}$
Brilliant blue	Chroma	blue	Glass *et al*. (1998 a), Mathers *et al*. (2000)	
Duasyn Blue	Clariant	blue	EN 12761 (2001)	*: 20-45 $g.L^{-1}$ **: 4×10^{-4} $g.L^{-1}$
Erythrosine		pink	Parkin *et al*. (1985), Cross *et al*. (1997), Murray *et al*. (2000)	
Green-S	Chromatech, Sensient	green	Cross *et al*. (1997), Miller and Smith (1997), Murphy *et al*. (2000), Murray *et al*. (2000)	
Lissamine Green		green	Gilbert and Bell (1988), Cross (1991 a)	
Nigrosin	Bayer	black		*: 20 $g.L^{-1}$ **: 0.5 $mg.L^{-1}$
Orange G	BDH Ltd.	orange	Gilbert and Bell (1988), Phillips and Miller (1999)	Resolution: 0.5 µL
Sunset Yellow		yellow	Glass *et al*. (1998 a), Mathers *et al*. (2000)	
Tartrazine (E102)	Unilex Exports Ltd.,	blue, yellow	Richardson *et al*. (1989), Cross *et al*. (1997), Pergher *et al*. (1997), Murray *et al*. (2000), Pergher (2001)	*: 70 $g.L^{-1}$ **: 2×10^{-7} $g.L^{-1}$
Water Blue		bleu	Parkin *et al*. (1985)	

*: solubility; **: detection limit

C. Real pesticides

To avoid the problems associated with dye degradation, different researchers used *real pesticides* - e.g. carbaryl (MacCollom *et al*., 1986), methoxychlor (Ware *et al*., 1969), permethrin (Fox *et al*., 1993 b), azinphosmethyl (Hall *et al*., 1975), malathion (Miller *et al*., 2000 b), Asulam (Robinson *et al*., 2000) - and gas chromatography in their drift investigations. Recently, Carlsen *et al*. (2006 a; b) studied droplet and vapour drift of 10 herbicides after tractor spray application. Other researchers using real pesticides as tracers are Miller *et al*. (2000 b) and Wittich and Siebers (2002).

D. Metal ions

The earliest examples of the use of metal ions as spray tracers arose from the use of copper as the analyte for the measurement of deposits of metal containing fungicides such as copper oxychloride (Large *et al*., 1946; Williams & Morgan, 1954; Herrington *et al*., 1981). The more specific application of simple metal salt to spray tracing was introduced by Akesson and Cowden (1978) and Yates *et al*. (1976) who measured strontium chloride or manganese sulphate spray deposits by atomic absorption spectroscopy (AAS). Byers *et al*. (1984) returned to the use of copper, but in a chelated form. Dobson *et al*. (1983) used dysprosium and neutron activation analysis as a method to measure spray drift.

Table 2.13: Overview of different metal ions used as tracers found in literature

Product	Manufacturer	Analysis method	References	Remarks
Metal chelates (Mn, Co, Mo, Zn, B, Sr, etc.)	BMS Micro-Nutrients, Ciba Specialty chemicals	Inductively Coupled Plasma (ICP), atomic absorption spectroscopy (AAS)	Derksen and Gray (1995), Murray *et al*. (2000), Cross *et al*. (2001 a; b), Langenakens *et al*. (2002), Nuyttens *et al*. (2004 a; b), Brusselman *et al*. (2005)	*: >1 $g.L^{-1}$ **:5-20 ppb
Copper Hydroxide	GFS chemicals, Agpro	colorimetry	Salyani and Whitney (1988)	Stable, not photosensitive, less sensitive and less fast
Dysprosium like tracer		neutron activation analysis	Dobson *et al*. (1983)	**: 1.62×10^{-3} µg/filter paper High sensitivity, safe use in the field, high speed of analysis, low cost, requires nuclear reactor
Metallic salts ($MnSO_4$, NaCl, $SrCl_2$)	Brenntag N.V., Kemira	atomic absorption spectrometry	Yates *et al*. (1976), Akesson and Cowden (1978), Brusselman *et al*., 2005, De Schampheleire *et al*. (2006 c)	

*: solubility; **: detection limit

The full potential of metal ion analysis for multiple tracer studies was realised by Travis *et al*. (1985) when they described a technique for determining deposits on apple leaves for following applications of copper, iron, manganese and zinc as their ethylenediaminetetra-acetic acid salts (EDTA). These metal chelates are easily available as foliar nutrients. Different other researchers like Derksen and Gray (1995), Murray *et al*. (2000), Cross *et al*. (2001 a; b) and Nuyttens *et al*. (2004 a; b), also used different types of metal chelates (containing zinc, manganese, borium, etc.) as tracers, and measured deposits by AAS or Inductively Coupled Plasma analysis. However, these methods often involve complex, expensive and time-consuming processing, which is undesirable when large numbers of samples must be processed. On the other hand, metal ions are photostable, water-soluble, inexpensive and can be measured in solution at concentrations down to 100 $ng.L^{-1}$. An overview of different types of metal ions used as tracers is presented in Table 2.13.

2.3.1.4. Image analysis

Besides the use of tracers and collectors, the amounts of spray deposit can be measured by means of image analysis. Image processing and analysis techniques lend themselves to automating the visual analysis of spray deposits. Kranzler *et al*. (1985) developed software for analysis of spray deposits. Their algorithms automatically selected gray-level thresholds, compensated for uneven lighting, established connectivity of image blobs and calculated size and area statistics. Last *et al*. (1987) established that the lack of adoption of available image analysis techniques by the pesticide application industry was due to the high cost of the equipment. They developed a low-cost system for analysing spray deposits on water-sensitive cards (Spraying Systems Co.). These water-sensitive papers provide a very popular technique for rapidly assessing spray coverage in the field and have been used among others by de Snoo and de Wit (1993; 1998). However, droplets smaller than 50 µm do not create a detectable stain on the water-sensitive paper and these papers will turn blue under high humidity. Moreover, a spread factor must be used to calculate the actual droplet that created a particular stain size. Hoffmann and Hewitt (2005) compared three imaging systems for water-sensitive paper and concluded that there were high correlations between the systems for the droplet spectra parameters $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$.

Sagi and Derksen (1991) evaluated several image processing algorithms for detecting spray drops on poinsettia leaves. Each algorithm used edge detection, followed by thresholding using a user-specified parameter and contour following. Image analyses were linearly correlated with spectrophotometer analyses of deposits on leaves. Franz (1993) developed software to analyse images of spray deposits on planar surfaces automatically. Using image analysis, problems might occur with overlap of droplets (Williams *et al*., 1999) and camera resolution. Mourougou-Candoni *et al*. (1999) formulated an equation to calculate the spread factor of droplets. This spread factor expresses the ratio between the droplet diameter before and after impact.

2.3.2. Spray quality experiments

Schick (1997) presented a detailed overview of different drop size sampling techniques, drop size analyzers and measuring protocols.

2.3.2.1. Sampling techniques

As described by Schick (1997), there are two different types of drop size sampling techniques which are the *spatial sampling technique* and the *flux sampling technique*.
As presented in Figure 2.14, with the *spatial technique* a given measurement volume containing droplets is sampled instantaneously. This technique is appropriate for application such as gas conditioning, cooling, or similar processes.
With the *flux technique,* also known as temporal, individual droplets passing through a cross-section are examined during an interval of time. This technique is appropriate for applications requiring an accurate spray deposition such as painting and agriculture.

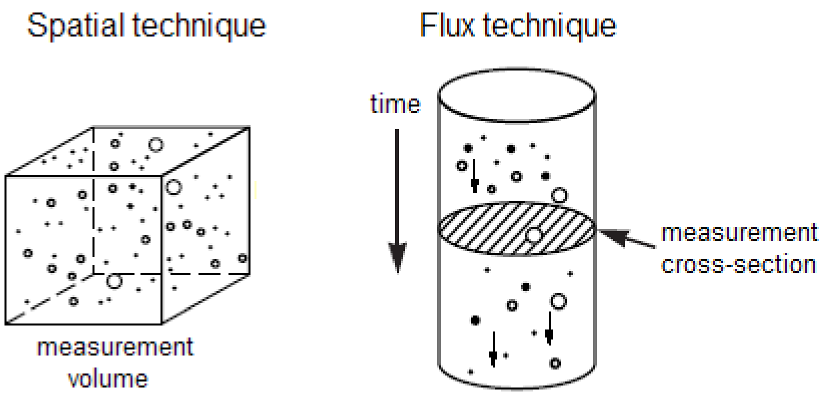

Figure 2.14: : Spatial and flux sampling technique (Schick, 1997)

Sampling technique plays an important role in the interpretation and comparison of drop size data (Arnold, 1987; Schick, 1997). If all droplets in a spray have the same velocity, the flux and spatial distribution are identical (Schick, 1997; Teske *et al*., 2000). In practice, the spatial technique will generally report smaller droplets than the flux technique because small droplets are slower. By dividing the number of samples in each class size by the average velocity of the drops in that size class, the flux distribution is transformed to a spatial distribution (Schick, 1997).

2.3.2.2. Drop size analyzers

Most drop size analyzers use non-intrusive optical methods to characterize sprays and thus they do not influence the spray behaviour during testing (Schick, 1997). Optical methods can be subdivided in two categories: *imaging* (photography and holography) and *non-imaging*. Non-imaging methods fall into two classes: those measuring a large number of droplets simultaneously on the one hand, and the single particle counters on the other hand.

These techniques are capable of producing huge amounts of useful and informative data, but it is also clear that two independent systems may give slightly different results (Arnold, 1987; Dodge, 1987; Young & Bachalo, 1987; Reeves & Womac, 1992; Steinke *et al*., 1995, Tuck *et al*., 1997; Womac *et al*., 1999). Hence, variations in spray droplet measurements done on different laser based instruments generated the need for a series of reference nozzles (§ 2.2.1.4) and proper testing procedures (§ 2.3.2.3).

Remark that many drop size analyzers also measure droplet fluxes and can therefore be used to measure spray drift (Miller *et al*., 1989 a; b). The main limitation of such systems for spray drift measurement is the small sampling volume, which, coupled with the high cost and complexity, means that it would often only be possible to obtain a single point drift measurement. The field use of such devices for drift measurements is therefore likely to be limited. They may, however, be useful in laboratory tests where the advantages of non-invasive sampling and high collection efficiency can be exploited.

The following is an overview of the most popular drop size analyzers (Schick, 1997).

A. Optical imaging analyzers

Optical imaging analyzers, also referred to as Particle/droplet imaging analyzers (PDIA), are based on the spatial sampling technique and belong to the optical imaging category. A schematic overview of a typical optical imaging analyzer is shown in Figure 2.15.

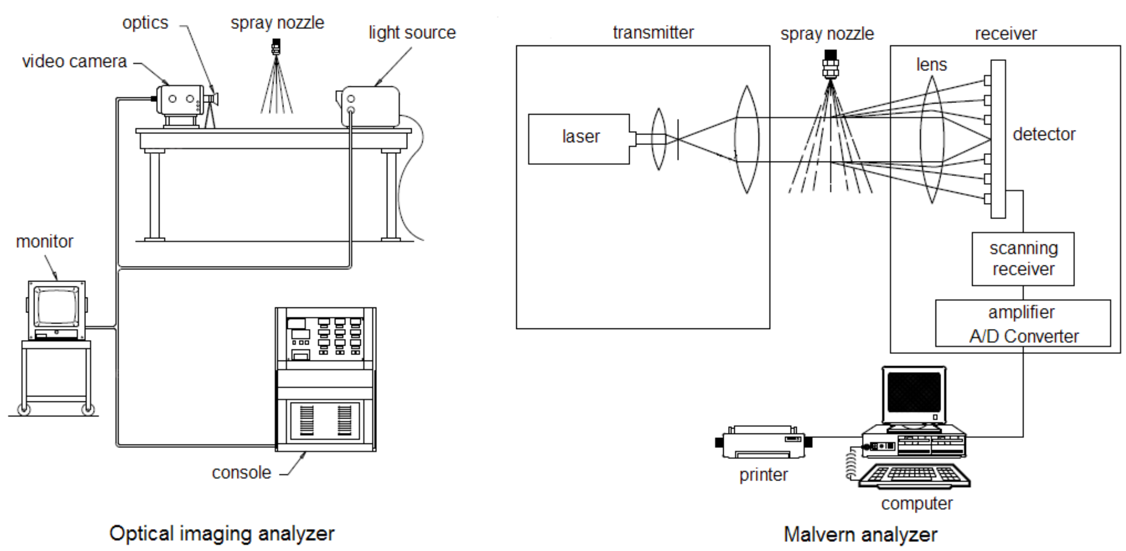

Figure 2.15: Typical Optical imaging analyzer (left) and Malvern Analyzer (right) (Schick, 1997)

This technique is based on the automated analysis of digital images of the spray. A very short flash of light illuminates a diffusing screen to back illuminate the subject. A digital camera with a microscope lens captures images of the subject. Different magnification settings can be used to provide a very wide range of droplet sizes to be measured. Image analysis software analyses the images to find drop size. Also shape data for the particles can be measured and recorded. By using dual laser flashes in short succession and measuring the movement of the particle, it is possible to measure particle velocity. Information on spray geometry can be provided by switching to light sheet illumination. The most common PDIA in use is the Visispray developed by Oxford Laser and used among others by Whybrew *et al*. (1999), Powell *et al*. (2002) and Kashdan *et al.* (2007). This system measures cone angle, drop size and drop velocity and other key parameters of the spray. Herbst (2001 a) and Kashdan *et al*. (2004 a; b) made comparisons of the PDIA, PDPA and Laser Diffraction and found good correlation between the results.

B. Laser diffraction analyzer

A laser diffraction analyzer is a spatial, non-imaging sampling device which operates by directing a laser beam unobtrusively through a spray cloud. Spray droplets diffract the light through different angles according to droplet size as they pass through the analyzer sampling area. The technique is based on measuring the scattered light intensity caused by the drops using semicircular photodiodes. From the light intensity distribution, the droplet size spectrum of an entire spray cloud is computed. Droplet velocities cannot be measured. The most common laser diffraction analyzer is the Malvern analyzer which has been used by different researchers like Barnett and Matthews (1992), Matthews (1992), Hanks (1995), Mueller and Womac (1997), Etheridge *et al*. (1999), Womac *et al*. (1999), Derksen *et al*. (1999), Teske *et al*. (2000), Nicholls *et al*. (2004) and Stainier *et al*. (2006 a). A schematic overview of this type of equipment is shown in Figure 2.15.
The method is simple and fast and requires the least skill by the operator compared with other systems. The measuring range is 1.2-1800 µm, although recently some manufacturers have increased the measurement range up to 3000 µm.
This instrument is best suited for measuring small capacity air atomizing, hydraulic and flat fan spray nozzles, and is useful for comparisons and quick evaluations of prototype nozzles. The most serious limitation of this technique is known as multiple scattering. Multiple scattering occurs when spray densities are too high; the light may be scattered by multiple drops before reaching the detector. This introduces errors in computing the drop size distribution. Others like Picot *et al*. (1993) attribute differences between laser diffraction analyzers and other measuring devices to spatial sampling errors associated with laser diffraction analyzers.

C. Optical array probes

Optical array probes are flux-sampling, non-imaging instruments falling into the single particle counter category. A schematic overview of the PMS-OAP probe is shown in Figure 2.16. With this type of instruments, droplets passing a sampling plane (created by a low-power laser beam) are sized and counted by measuring the amount of laser light (using a photodiode array) shadowed by the drops. Moreover, information is provided that can be used to determine droplet velocities. Measurement range for these probes can vary from 100-12 400 µm and they are best suited for large capacity nozzles (Schick, 1997). The most common optical array probe in use is the PMS-OAP (Particle Measuring Systems - optical array probe; Knollenberg, 1970) used among others by Matthews (1992). A conversion between PMS-OAP and Malvern laser diffraction data has been provided by Teske *et al*. (2000).

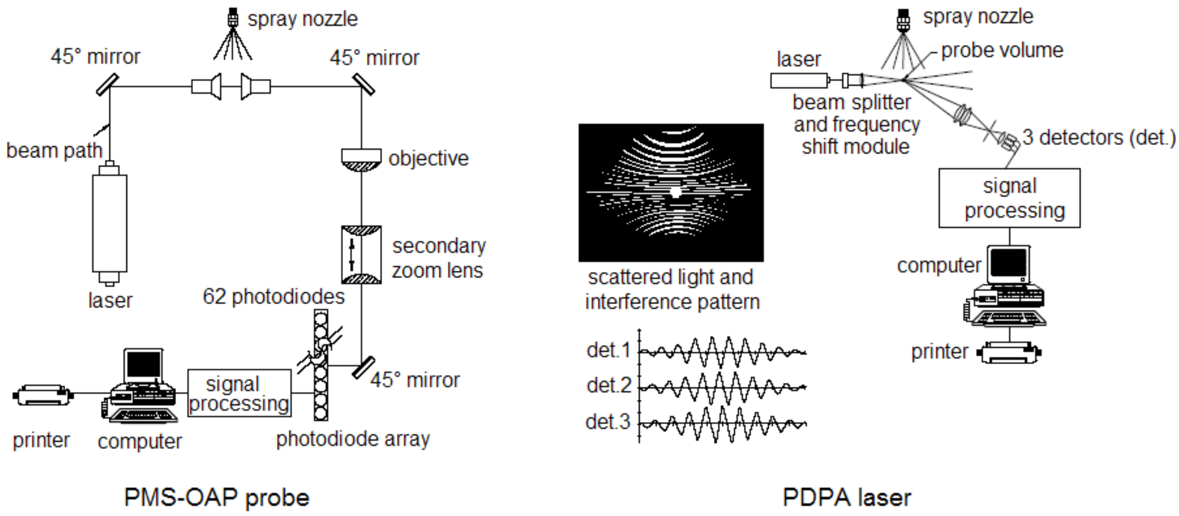

Figure 2.16: PMS-OAP (left) and PDPA (right) (Schick, 1997)

D. Phase doppler particle analyzer (PDPA)

Phase doppler particle analyzers (PDPA) are flux-sampling, non-imaging instruments, falling into the single particle counter category as described by Schick (1997). This technique is used in this research and described in detail in section 3.2.4. The PDPA produces two low-power laser beams crossing each other at a point referred to as the probe volume. The scattered light created from a droplet passing this measuring volume forms an interference fringe pattern. The frequency of this scattered light is proportional to the droplet velocity while the spatial frequency of the interference fringe pattern is inversely proportional to the drop diameter. Depending on the optical configuration, PDPA measures sizes in the 0.5-10 000 µm range. This measuring technique is best suited for complete spray evaluation where drop velocities are required for a wide range of nozzle types.

The most common phase doppler particle analyzer in use is the PDPA manufactured by Aerometrics Inc. used among others by Bachalo and Houser (1984), Matthews (1992), Wolf *et al*. (1995), Lund and Matzen (1996), Downer *et al*. (1997), Sidahmed *et al*. (1999) and Butler Ellis and Tuck (1999). Tuck *et al*. (1997) compared measuring results of hydraulic flat fan nozzles from a PDPA and a PMS-OAP. PDPA gave consistently lower *VMD* values and higher droplet velocities than PMS-OAP. PMS-OAP gave lower percentages of spray volume in droplets less than 100 µm while the PDPA indicated some large droplets that were not detected by the PDPA. A schematic overview of the PDPA is shown in Figure 2.16.

A possible complication might occur using a PDPA when the droplets contain internal structure, such as emulsion droplets or air inclusions because phase doppler analysis relies upon light passing through each droplet. Work carried out by Tuck *et al*. (1997), showed that the distributions measured with PMS-OAP and PDPA can be similar, even when emulsion droplets, air inclusions or other interfaces were present, indicating that the PDPA was measuring correctly. However some combinations of ingredients led to such a high density of internal air/liquid or liquid/liquid interfaces that the PDPA distribution began to show signs of inaccuracies (Tuck *et al*., 1997). It is not known what determines whether the internal droplet structure will affect light-scattering and therefore it is important to take great care in measuring spray liquids other than water.

E. Image analysis

While droplet number may be quite easily monitored using water-sensitive-paper, as described in 2.3.1.4, it is much more complex to obtain droplet size data from water-sensitive paper and image analysis. That is why Satow *et al*. (1993), Smith *et al*. (2000 b) and Harz and Knoche (2001) used a technique where droplets are suspended between two layers of silicone oils of different viscosity for droplet size measurements. This technique is particularly useful for small-scale laboratory studies. Wolf *et al*. (1999) and Wolf and Frohberg (2002) used the WRK DropletScan™ technology (Whitney, 1997) and water-sensitive paper to measure droplet sizes. Other researchers like Pessoa and Chaim (1999), Chaim *et al*. (1999; 2002) and Kirk and Hoffmann (2002) used similar image analysis software to measure droplet sizes. May (1950) and Matthews (1992) used a light microscope to measure impaction craters on magnesium oxide-coated slides to estimate droplet size.

Each analyzer is best suited for specific types of testing. Whereas some overlap in measurement range might be present between these instruments, it is virtually impossible to compare data from these different instruments without a clear understanding of the test conditions and methodology (Dodge, 1987). That is why Arnold (1987) and Teske *et al*. (2000) studied the practical conversion of droplet size spectra from PMS-OAP to the Malvern laser. Similar studies were carried out to convert temporal samples to spatial samples (Arnold, 1987) and vice versa (Chapple *et al*., 1993). Hewitt and Valcore (1995) measured similar droplet sizes between a Malvern and a PDPA instrument when a 37 $km.h^{-1}$ airstream was applied to the Malvern measured droplets.
Similarly, it is very difficult to compare data from various nozzle manufacturers even when the same type of instrument was used, because optical configuration and data sampling methods might differ. Finally, proper calibration and maintenance of the measuring equipment cannot be overlooked. Properly scheduled calibration tests are important, particularly in laboratories where many researchers use the equipment.
Other methods, which mostly rely on post-application collection, such as spray-sensitive cards and papers, can generate errors due to sampling and collection bias.

2.3.2.3. Protocols

A. Statistics

Drop size analyzers collect and record data that is typically presented as a drop size distribution. The most common drop size distribution functions are the *Rosin-Rammler* distribution function (Schick, 1997), the *ASTM Standard E799-92* analysis (Schick, 1997) and the *log normal distribution* (Parkin & Siddiqui, 1990). The ASTM Standard E799-92 is best suited for use with analyzers that are classified as single particle counters, such as the PMS and PDPA analyzers. Other drop size distributions that are used are the *upper limit log normal* and the *model independent* distribution. Regardless of what drop size distribution function is used, they all essentially perform the same task. The result is a mathematical drop size distribution from which a collection of characteristic or mean diameters can be extracted (§ 2.2.1.1).

B. Sampling strategy

Because the size distribution of droplets in agricultural spray nozzles depends on the position within the spray (Chapple & Hall, 1993; Butler Ellis *et al*., 1997), it is important to ensure that the strategy which is chosen for quantifying a spray provides a representative sample of droplets, both in terms of numbers of droplets detected and the position at which they are measured or the scanning strategy. At this moment, there are efforts to define an international standard for the measurement and classification of droplet size spectra from atomizers making use of reference sprays (ISO/CD 25358, 2007).

Number of droplets

Different authors noted the importance of collecting sufficient droplets from the spray to ensure that a representative sample is taken. Parkin (1993) suggested that satisfactory results were unlikely to be obtained with a PMS-OAP with samples containing less than 2000 droplets. Adams *et al*. (1990) recommended 10 000 droplets with a PDPA.
Tuck *et al*. (1997) concluded that the number of droplets required for an adequate sample depends upon the spray itself, the instrument used and the analysis technique. For flat fan nozzles, this was approximately 3000 for the PMS-OAP and 13 000 for the PDPA.

Scanning strategy

Tuck *et al*. (1997) evaluated different scanning strategies. They concluded that neither a single position nor a one-dimensional scan is necessarily representative of the whole spray from a flat fan nozzle. If information about the whole spray is required, scanning the whole spray cross-section is necessary because the spray is not homogeneous (Butler Ellis *et al*., 1997; Lund & Matzen, 1996; Chapple & Hall, 1993).
When measurements of the whole spray or over a large region of the spray are required, a scanning pattern has to be devised to ensure that the region is sampled adequately, either by scanning parallel to the short axis or to the long axis. Chapple and Hall (1993) demonstrated that there was some variation in *VMD* with position for a TeeJet XR 8003 nozzle, but concluded that a single scan along the long axis gave an adequate representation of the whole spray. Butler Ellis *et al*. (1997) on the other hand, indicated that a single long axis scan may not be representative in all circumstances because changing the spray liquid can alter the distribution of droplet sizes and the thickness of the spray. They preferred scanning parallel to the short axis of the fan.
The minimum number of scans required to adequately sample the full spray will depend on the variation of spray characteristics along the axis. In practice, the rate at which the droplet size distribution changes with horizontal position will dictate the step length and the speed of the transporter will determine the duration of the measurement and the number of droplets detected. Measurements of the effect of scan speed showed no differences between 1 and 50 $mm.s^{-1}$. Hence, the scan speed can be adjusted within these limits to minimize the experiment duration, providing an adequate number of droplets are measured as mentioned above (Tuck *et al*., 1997).

Nozzle height

Lake and Dix (1985) found that there was very little effect of nozzle height above the measurement volume on *VMD* when measured with PMS-OAP. Young (1990) showed that the *VMD* directly below the nozzle decreases with height when measured with a PMS-OAP. This is to be expected in case of the PMS-OAP because the spray density decreases as the height increases, allowing the PMS-OAP to take a more representative sample. Measurements carried out by Tuck *et al*. (1997) showed that there is a significant increase in *VMD* with height. It was originally thought that the reason for this might be that the droplet velocities decline with distance below the nozzle, making the droplet velocities increasingly small compared to the range of velocities measurable, leading to a biased sample. However, reducing the velocity range by reducing the bandwith of the instrument showed little change in *VMD*, so it is unlikely that this is the cause. Chapple and Hall (1993) showed that an Aerometrics PDPA underestimated considerably the volume flux in the centre of the spray, suggesting that it is possible that the PDPA samples less efficiently at high densities. However, measurements from Tuck *et al*. (1997) did not demonstrate this. In conclusion, it is important when making comparisons between sprays that they are always sprayed at the same height. Spray quality experiments performed in this study are described in Chapter 3.

2.3.3. Wind tunnel approaches

Different approaches have been used to study spray drift, but field experiments, although covering the widest range of parameters, are time-consuming and expensive. Moreover, the number of variables involved in field studies makes interpretation difficult, so wind tunnel studies have been advocated (Parkin & Wheeler, 1996; Walklate *et al*., 2000; Murphy *et al*., 2000) to calculate a *relative drift risk factor* or a *drift potential factor*. The main potential advantage of wind tunnel tests is that driftability experiments can be made with different spraying systems under directly comparable and repeatable conditions. High turbulence and short sampling periods may give variability of collected drift according to Miller (1993).

Wind tunnel environments can be matched approximately to field conditions either in terms of the air velocity profile between the floor of the tunnel and the spraying system or in terms of air turbulence levels. Wind tunnel arrangements have been devised that create downwind conditions in which spray drift studies can be conducted (Davis, 1987) with either realistic velocity profiles or turbulence levels. It is however, difficult to achieve both the correct velocity profiles and turbulence levels in relatively small and simple wind tunnels.

There is likely to be some interaction between the airflow conditions and the spray drift sampling system. For example, laminar flow conditions may give streaming of the drift and high local concentrations in some regions of the collector, which may then saturate the collector surface and give inaccuracies when integrating results to estimate total drift levels. Alternatively, high turbulence levels and short sampling periods (needed to prevent collector saturation) can give variability in the amounts of collected drift in wind tunnel experiments. A major limitation with all wind tunnel experiments is the physical size of the spraying system that can be studied.

Wind tunnel measurements have been performed to study air-assist sprayer operating parameters (Bayat *et al*., 1999), effect of formulation and adjuvants (Thacker & Macaskill, 1997; Stainier *et al*., 2006 a) and in some cases, wind tunnel studies are combined with PDPA measurements (Farooq *et al*., 2001 a; b; Herbst, 2001 b). In this study, a whole series of wind tunnel measurements were carried out which are described in Chapter 4.

2.3.3.1. Drift potential factor

The classification of sprays according only to droplets size does not take into account the velocity, density, air-entrainment or trajectory of the droplets in the spray clouds. For a given type of nozzle, these factors may fall within a sufficiently narrow range to support the use of a classification based only on droplet size. However, many researchers have shown that such classification does not always describe accurately the performance of many ground spray drift-reduction nozzle systems with regard to spray drift. For example, Walklate *et al*. (1994) showed that relative drift predictions using the percent of the spray volume with a diameter less than 100 µm did not give a fair representation for a dual-orifice flat fan nozzle, a twin fluid nozzle and a hot gas applicator nozzle. Similar results were found by Miller *et al*. (1991). That is why techniques have been developed and used for assessing drift risk or potential drift from agricultural nozzles in wind tunnels by different researchers.

Initial studies with a range of nozzles spraying in a wind tunnel have shown that differences in the risk of drift could be related to measures of the airborne spray profile even when using different wind tunnel configurations and sampling methodologies (Western *et al*. 1989, Miller *et al*., 1989 a; Walklate *et al*., 1994). Results showed relatively good agreement between the quantities of airborne drift measured in different conditions particularly when they were normalised using results from the BCPC reference nozzles (Miller *et al*., 1995 b). The agreement was closest for measurements with wind speeds in the range of 2.0 to 2.5 $m.s^{-1}$ and carried out in wind tunnels which met defined criteria (Parkin & Wheeler, 1996). A test protocol for use when conducting wind tunnel tests to assess the risk of drift was proposed as a result of this work (Miller *et al*., 1993). Collaborative work between the 'Biologischen Bundesanstalt für Land- und Forstwirtschaf' (BBA, Germany) and Silsoe Research Institute (SRI, UK) showed that there were some limitations to this proposed protocol. The BCPC reference nozzles were used to define characteristics of cumulative airborne spray volume against distance below the nozzle and to define classes of drift risk assessment (Miller *et al*., 1995 b). However, results from a series of tests with different nozzles systems (e.g. cone nozzles, spinning discs) gave characteristics which did not have the same form as those for the reference nozzles. Moreover, substantial differences were found between single nozzles and multiple nozzles mounted on a boom because of the change in airflow patterns around and through the spray structure (Miller *et al*., 1995 b). The SRI wind tunnel was used in this research and is described in detail in section 4.2.1.

That is why Southcombe *et al*. (1997) recognised that any comparative analysis of the airborne spray profiles downwind of a test nozzle in a wind tunnel need to take into account the total volume and the vertical distribution of airborne spray. They suggested two possible approaches for use in a standardised protocol, namely:

1. to make measurements at a distance that is far enough away downwind from the nozzle such that the effects due to spray structure and droplet size distribution have settled. This method has advantages in terms of a simplified analysis and a result that can be closely related to the field performance of a nozzle or a boom sprayer but it requires a large wind tunnel facility and may not adequately address the assessment of drift risk close to the sprayer,
2. to make measurements closer to the nozzle and use a comparative method of analysis which accounts for the total airborne spray volume. This method can be used with a smaller tunnel system. Southcombe *et al*. (1997) proposed to establish a comparative scale based on a calculation of the first moment of the airborne drift profile measured at a distance of 2.0 metres downwind of the nozzle. Reference nozzles can be used to define the categories for this drift potential factor which can be calculated as follows:

$$DPF = \sum_{i=1}^{n} V_i . h_i \qquad (2.7)$$

where V_i is the volume of airborne spray at height h_i and n is the number of collector lines.

Other studies to develop protocols for wind tunnel tests have recently been undertaken by Phillips and Miller (1999), Herbst and Ganzelmeier (2000) and Walklate *et al*. (2000). Herbst and Helck (1998), Herbst and Ganzelmeier (2000) and Herbst (2001 b) also combined wind tunnel measurements and a PDPA measuring set-up mounted on a traverse bar to be able to scan the whole wind tunnel section as illustrated in Figure 2.17. They calculated a Drift Potential Index (*DIX*) from parameters of vertical drift concentration in a section 2 m downwind from the nozzle. This *DIX* value was used to classify nozzles regarding spray drift potential in relation to a conventional flat fan ISO 03 nozzle at a pressure of 3.0 bar. Schmidt (1997) and Herbst (2001 b) concluded that *DIX* values correlate quite well with ground sediment values.

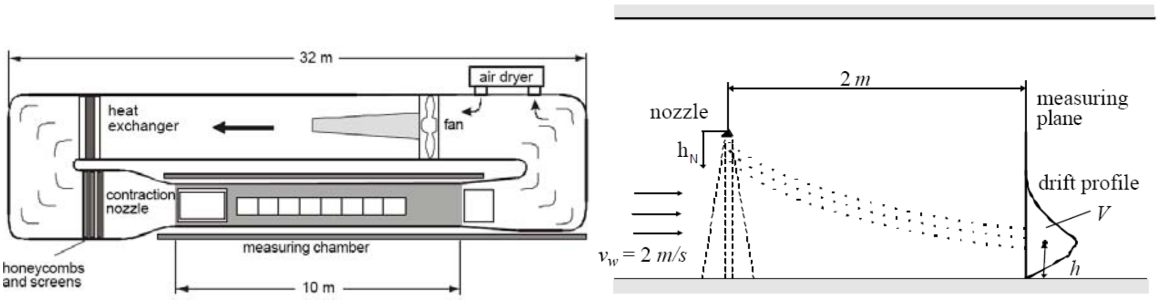

Figure 2.17: BBA wind tunnel (left) and experimental arrangement for drift potential estimation (right) (Herbst, 2001 b)

Miralles and Bogliani (1993) involved macroscopic evaluations of the wind effects on sprays emitted by nozzles in the laboratory. The technique is based on the comparison between the liquid distributions obtained on a patternator when the spray is subjected to a wind or not. This methodology has been used to compare the drift potential of nozzles at different pressures, heights and orientations.

Remark that Porskamp *et al*. (1999) and van de Zande *et al*. (2000 b) set up a classification of spray nozzles based on driftability through a combination of PDPA laser measurements (§ 2.3.2.2) and computer modelling (IDEFICS, § 2.4.2) and hence without any wind tunnel measurements. Droplet size and velocity data are used as an input for the IDEFICS spray drift model to calculate downwind drift deposits. Spray drift reduction of nozzle-pressure combinations is expressed as a percentage reduction compared to a reference nozzle. They also concluded that spray drift is not only correlated with droplet sizes but also with the spray angle and droplet velocities, which was confirmed by Butler Ellis and Bradley (2002). Balsari *et al*. (2006) proposed the use of a test bench to classify boom sprayers according to drift risk also without use of a wind tunnel.

Finally, at the moment of writing this work, efforts are made to unify the different methods described above in one international standard method (ISO/DIS 22856, 2007).

2.3.4. Spray drift field experiments

The comparison of drift data from drift studies conducted by different researchers is often very complex because different techniques, tracers, experimental design and test conditions yield different results. Numerous researchers already carried out field drift measurement in one way or another like Bode *et al*. (1976), Göhlich (1983), Permin *et al*. (1992), Fox *et al*. (1993 a), Thacker *et al*. (1994), Bouse *et al*. (1994), Baldoin *et al*. (1998), de Snoo and de Wit (1998), Praat *et al*. (2000), Cross *et al*. (2001 a; b), Heijne *et al*. (2002), Klein and Johnson (2002), Weisser *et al*. (2002), Richardson *et al*. (2004), Bjugstad and Sønsteby (2006) and many others. To harmonize the different drift measurements, ISO Standard ISO 22866 (2005) 'Methods for field measurement of spray drift' has been developed. An overview of the most important elements related to this specific research is given. For full details, the ISO norm should be consulted. This International Standard was prepared by Technical Committee ISO/TC 23, Tractors and machinery for agriculture and forestry, Subcommittee SC 6, Equipment for crop protection, of which the author of this work is a member. At the moment of writing this work, a standard specifying the drift classification of spraying equipment is under development (ISO 22369-1, 2006; ISO/DIS 22369-2, 2007). Results of the field drift measurements performed in this study can be found in Chapter 5.

2.3.4.1. Methods for field measurement of spray drift (ISO 22866, 2005)

This International Standard ISO 22866 (2005) establishes principles for the field measurement of droplet spray drift during application from all types of equipment designed for applying plant protection products and includes detailed specifications related to among other things horizontal boom sprayers. In this standard *spray drift* is defined as the quantity of plant protection product that is carried out of the sprayed (treated) area by the action of air currents.
Moreover, the *swath width* or boom width of a horizontal boom sprayer is specified as the distance between the outermost nozzles on the boom plus half the average nozzle spacing along the boom at each end. The *directly sprayed area* is the area for which the spray treatment is intended. Both terms are illustrated in Figure 2.18.

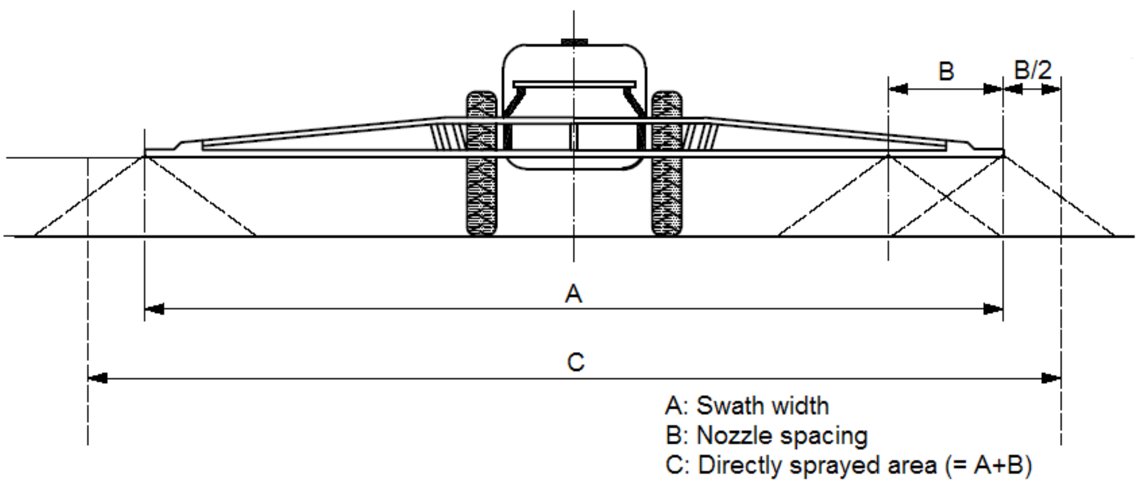

Figure 2.18: Swath width and directly sprayed area for boom sprayers (ISO 22866, 2005)

An overview of the essential elements described in this standard for horizontal boom sprayers is presented.

A. General

- A spray drift measurement comprises the application of a traceable material, to a defined, directly sprayed area of crop at a measured forward speed along tracks arranged at right angles to the mean wind direction. Spray drift shall be determined by sampling in a defined downwind area.
- The spray liquid shall have physical properties representative of liquids typically used in the application of plant protection products.

B. Trial site and conduct of a trial

- The trial site shall be in an exposed area with a minimum of obstructions that could influence the airflow. The downwind area shall be bare soil or have short vegetation (maximum height 7.5 cm) over which assessments of airborne spray drift and/or sedimenting spray drift shall be made.
- The width of the directly sprayed area depends on the necessary upwind distance from which spray drift may add a significant contribution (> 10% of total measured drift) toward the total spray drift loss from the area, and should be at least 20 m.
- The length of the directly sprayed area shall be at least 50 m long or twice that of the largest downwind sampling distance.
- Each measurement shall involve sampling ground and/or airborne drift and assessments of the spray deposits in the directly sprayed area.
- Measurements with a defined reference spraying system shall be included when comparative measurements are to be made. Some researchers used a dual tracer technique like Courshee (1959), Bode *et al*. (1976), Johnstone (1977) and Gilbert and Bell (1988). This dual tracing technique consists of two separate spraying systems mounted on the same tractor, permitting the exposure of two different sprays to the same climatic conditions.
- Measurements shall be made at wind speeds of at least 1 $m.s^{-1}$, a mean wind direction of 90° ± 30° to the spray track and a temperature between 5°C and 35°C.
- Meteorological conditions shall be continuously measured (at a frequency of least 0.1 Hz). These measurements include the wind velocity at one height, the temperature difference between two heights, the mean air temperature and humidity and the wind direction.

C. Measurements of spray drift

- *Sedimenting spray drift* shall be sampled using horizontal collection surfaces placed at a level corresponding to the top of the vegetation or crop. These collectors shall have a good retention and recovery of the tracer used.
- At each sampling distance, a minimum of two discrete horizontal samplers shall be used with a minimum sampling area of 1000 cm^2.
- Drift measurements should be made at distances of at least 5 m and 10 m from the directly sprayed area.
- Measurements shall be replicated at least three times in wind conditions that are as similar as is practicable.

2.4. Spray drift modelling

Modelling spray drift has always been an important research topic, mainly to simplify field tests which are very difficult and expensive. The use of computer models and mathematical simulations could be an important complement to heavy tests, where many environmental variables and technical conditions are in constant change, in time as well as in space (Gil & Sinfort, 2005). Field experiments have the limitation that weather conditions, especially wind, cannot be controlled throughout the test period and can vary during a single pass with a sprayer. Terrain and vegetation also often vary among drift measuring sites and these can influence local wind conditions and drift deposits. There is usually considerable variation among drift deposits even between consecutive passes of a sprayer (Fox *et al*., 1993 a; Salyani & Cromwell, 1993). Computer simulation provides a means of determining the relative effects of various factors on spray drift.
Nevertheless, drift models cannot be considered as a substitute for determination in the field and the laboratory, but rather as a very powerful complement that aids in understanding of the phenomenon, as well as adapted practice implementation in order to decrease the contamination risks. These models can be used to predict the behaviour of droplets for different input factors like wind speed, droplet size, spray boom height, etc.
Deposition modelling of pesticide sprays presents a substantial challenge in detail because it is critically dependent on the drop size distribution but atomization remains a very difficult problem to model. Beyond the nozzle, the releasing vehicle may have an important effect on the position of droplets. Finally, transport through the atmosphere beyond the effects of the release mechanism and machinery must be addressed.
Much effort has been made to assess and model spray drift through analogy between mathematical procedures, experiments in wind tunnels, and limited field tests. Helck and Herbst (1998) proposed a drift index which correlated drift theory with wind tunnel and field tests.

Some researchers mention four different types of models i.e.: (1) full physics models that attempt to utilize a Navier-Stokes form of the scalar transport equation, (2) hybridized physical models that explicitly handle parts of the physics but parameterize other parts, (3) Gaussian models that make a priori assumptions about the shape of the plume and the distribution of material within the plume and (4) pure statistical models.
In reality, most applied drift models utilize components from some or all of these model categories. That is why the most commonly reported models to predict droplet movements in the air during spraying have been divided between *plume, individual droplet trajectory* and *statistical models* (Miller & Hadfield, 1989; Holterman *et al*., 1997).

2.4.1. Plume models

Atmospheric dispersion models are mainly used to determine the displacement and deposition of drop clouds over medium or long-range distances (0.5-10 km) for aerial applications (Bache & Sayer, 1975; Reid & Crabbe, 1980), although recently reasonably good results have also been obtained for short-range drift (Kaul *et al*., 1996 b; Stainier *et al*., 2006 b). However, it is still difficult to describe short-range drift by plume models, mainly because of the problems to account for near-nozzle features of the spray cloud as well as the sedimentation of evaporating droplets.

This method can calculate pesticide concentrations at any geographical position from various factors, like atmospheric conditions (wind speed, direction, stability, temperature, etc.) and source characterization. These models can be used to estimate spray drift deposition in trade drift risk assessments settling from a point or line source (Cramer *et al*., 1972; Bache & Sayer, 1975; Teske *et al*., 1993; Barry *et al*., 1993; Tsai *et al*., 2005). De-Leeuw *et al*. (2000) defined it as a procedure by which predictions of an air quality indicator are made. Plume models are based on the prediction of the concentration of a pollutant emitted from a given source.

The most common model applied to sprayed particle dispersion is the 'Gaussian plume' or '*the Gaussian Diffusion Model*'. Raupach *et al*. (2001 a) presented a simple model to determine contaminant transport, based on mass conservation and Gaussian-plume assumption for spray and vapour transport of agricultural chemicals in aerial application to environmental receptors. Raupach *et al*. (2001 a), Craig *et al*. (1998) and Craig (2004, GDS model) developed plume models for drift assessment in aerial applications, and the validation results showed a good correlation with measurement of downwind deposits for different droplet sizes and wind conditions. Thus, it would be possible to infer that this model would be useful to consider buffer zones for aircraft applications. Nevertheless, additional information related to stability effects, collection efficiency, evaporation and canopy effects as well as chemical and physical properties of applied products is required.

The advantages (simplicity) and drawbacks (resolution near application zones) are discussed in Thistle (2000) and Teske *et al*. (2002). These models are useful at longer ranges and have greater flexibility in accounting for the field source width effect and hence, they are useful for field source widths of several kilometres. Plume models are less suited for ground applications but are regularly used for aerial applications where the effects of complex topography and atmospheres are intentionally ignored (Craig, 2004). Droplet trajectory models are more suitable to model short-range spray drift.

2.4.2. Droplet trajectory models

Droplet trajectory models estimate the movements and positions of individual drops set under external physical forces. During their trajectory into the air, the droplets are exposed to several forces that affect their movement in the flow field. Assuming that all droplets are separated and with spherical form, and neglecting other forces and physical effects (with relatively little influence), the drag or aerodynamic force and gravity are the forces that influence the droplet motion (Smith, 1970; Reichard *et al*., 1992 b; Urip *et al*., 2002). From this description, the droplet trajectory can be calculated by applying a *Lagrangian approach*, which is described by several authors based on Newton's second law (F = m.a). The relaxation time of the drop is the characteristic time a drop needs to adapt to local airflow and to reach its sedimentation speed (v_s') as already described in section 1.3.2. It is defined by the ratio between drop mass and the air friction coefficient (Holterman *et al*., 1997; Teske *et al*., 2002). A well-known example of a Lagrangian spray deposition model is AgDRIFT® (Teske *et al*., 1997; 2002) (Table 2.14). The atomization model DropKick® is included in the AgDRIFT® model and the AGDISP model (Bilanin *et al*., 1989) is used as a basis for the AgDRIFT® model (Table 2.14).

When the liquid is forced through the opening in a typical hydraulic nozzle it creates a liquid sheet. The droplets are created from liquid sheet disintegration, and they move in the air-jet caused by the interaction of the spray plume and the surrounding air. Close to the nozzle, all drops move at the same speed, but as the air-jet decays, fine drops with their greater drag to mass ratio become detrained. They can then become influenced by atmospheric air movements and cause spray drift. Lower spray volumes usually require smaller orifice nozzles that, in turn, produce finer sprays and increase the potential for spray drift (van de Zande *et al*., 2003).

Several authors developed methods and mathematical procedures for predicting spray droplet trajectories as well as diameter change, combining individual motion drop equations with droplet evaporation theory (Goering *et al*., 1972; Williamson & Threadgill, 1974), using a *multiple regression method*, also described in section 2.2.4.5. Smith *et al*. (2000 a) used multiple regression procedures to develop models predicting spray drift from boom sprayers. Spray drift was most strongly related to the downwind distance, wind speed and nozzle height. In this study, droplet characteristics were not significantly related to spray drift.

Thompson and Ley (1983) developed a *random-walk model*, considering the droplet motion in a turbulent atmosphere with Gaussian distributions of air velocity. From this approach several authors developed or evaluated numerous mathematical equations and computational programs to predict spray droplet dynamics in field conditions (Miller & Hadfield, 1989; Walklate, 1992; Hobson *et al*., 1993; Smith and Miller, 1994; Mokebe *et al*., 1997; Cox *et al*., 2000), including successive improvements related to drop behaviour in the near nozzle region and downwind deposits. Model validation was made using a wind tunnel, and showed diverse results. Reichard *et al*. (1992 b) verified that the modelling procedures could be used to calculate spray drift distances for a wide range of spray droplet sizes and wind velocities. Based on a two-dimensional random-walk model, Hobson *et al*. (1993) investigated the effects on spray drift of nozzle size, angle and operating pressures for boom-mounted hydraulic nozzles over a range of meteorological and crop conditions. The results showed that measurement of droplet size, particularly the percentage of spray volume in droplets less than 100 μm in diameter, critically influenced spray drift. Drift was also shown to increase significantly in atmospheric conditions that promote droplet evaporation.

In spray applications, many factors such as airflow rate, crop type and development and spray configuration, affect drop turbulent trajectories from the nozzle to the target. That is why recent studies focused on the physical and mathematical description of these flows through the use of *Computational Fluid Dynamic* (CFD) software. In agricultural spray applications, the CFD codes (FLUENT® or CFX®) are commonly used to solve the turbulent flow using the Navier-Stokes mass and momentum equations, coupled with a standard k-ε turbulence model.

This software has been used by several authors to simulate spray applications (Reichard *et al*., 1992 a; Weiner & Parkin, 1993; Walklate *et al*., 1993; Zhu *et al*., 1994; Tsay *et al*., 2002 a; b; c; Sidahmed & Brown, 2001; 2002; Da Silva *et al*., 2006; Baetens *et al*., 2006; 2007), including a spatial model to take into account the effect of interactions between the airflow and crop (Xu *et al*., 1998; Da Silva *et al*., 2001; Farooq & Salyani, 2004). Reichard *et al*. (1992 b) and Zhu *et al*. (1996) verified the effectiveness of the CFD model to predict drop trajectories in turbulent flow through wind tunnel tests. Zhu *et al*. (1994) extended the range of simulated parameters to determine drift distances up to 200 m for field sprayers.

Although the models described above are very useful tools to estimate spray drop trajectories, they could give different results from real field data because of interactions with the crop as well as the temporal and spatial variations in environmental conditions.

These are very difficult and expensive to consider through mathematical and computational processes.
CFD codes used in turbulent flows have only allowed the study of the factors that affect drift processes, and the validation data are limited to specific and controlled conditions. Hence, an extensive field evaluation is still necessary, mainly to assess the effect of operational conditions (Gil & Sinfort, 2005). That is why a whole series of spray drift field experiments were performed in this study as described in Chapter 5.

2.4.3. Statistical models

Different sophistication levels of statistical models exist but all are based on a database of multiple field drift measurements (Smith *et al*., 2000 a). The quick and highly predictive level for many outdoor application conditions is the main advantage of this experimental approach. The main difficulty is to obtain the huge amount of good quality measurements needed as well as the high variability of the drift values. In general, statistical models are based on multiple regressions to study different independent parameters. That kind of models is used by the BBA in Germany (Herbst & Ganzelmeier, 2000) and EPA in the US (Teske *et al*., 1997)

An overview of different developed atomization and drift models is presented in Table 2.14.

Table 2.14: Overview of atomization and spray drift models

Name	Description	References
AGDISP	- Lagrangian model used for many other models e.g. AgDRIFT® - Verified for numerous applications over the years - Predicts, as a function of time, the path of spray released from a helicopter or airplane - Developed under a cooperative research between USDA Forest Service, NASA and US Army	Bilanin *et al*., 1981; 1989
AgDRIFT®	- Models aircraft, orchard and ground applications - Lagrangian model - Model output is off-target deposition as a fraction of the application rate - Based on previous model AGDISP - Primarily for risk assessment purposes - Developed under a cooperative research between US EPA, USDA, US Forest Service and SDTF (Spray Drift Task Force)	Teske *et al*., 1997; 2002
DRIFTSIM	- Visual basic language computer program, easy to use - Estimates mean drift distances of discrete sizes of water droplets discharged from nozzles on field sprayers - Interpolates values from a large database of drift distances for individual droplets calculated with FLUENT	Zhu *et al*., 1994; 1995
DropKick®	- Atomization model to estimate droplet size spectra for most hydraulic agricultural spray nozzles - Includes multiple linear regression, dimensional analysis and neural network analysis - Based on the SDTF atomization/physical properties database - Possibility to convert spray quality for ground applications to an aerial application equivalent - Included in the AgDRIFT® model	Hermansky, 1998; Teske, 1998; Esterly,1998

Name	Description	References
FLUENT®	- CFD code - Used to simulate various aspects of pesticide applications - Expensive, requires a lot of computational power, not easy to use	Reichard *et al.*, 1992 a; b; Weiner and Parkin, 1993; Walklate *et al.*, 1993; Zhu *et al.*, 1994; Brown and Sidahmed, 2001; Sidahmed and Brown, 2002; Tsay *et al.*, 2002 a; b; c
GDS model	- Gaussian plume model - Calculates aircraft drift buffer zones - Computationally fast and able to provide real-time prediction in the cockpit - Based on expressions developed by Lawson (1978) and Spillman (1984)	Craig, 2004
IDEFICS	- IDEFICS: IMAG program for Drift Evaluation from Field Sprayers by Computer Simulation - Mixed 2-3 dimensional random walk model to quantify spray drift from conventional field sprayers in crosswind - Phase-Doppler anemometry (PDA) used to measure the distribution of drop size and velocity in the spray cone - Compared with experimental data	Holterman and van de Zande, 1996; Holterman *et al.*, 1997; 1998
IMAG Drift Calculator	- Tool to quantify drift to surface waters near a sprayed field or orchard - Uses statistically obtained regression curves	
MOPED	- MOPED: MOdel for PEsticide Drift - Screening model to predict the spray drift from airblast sprayers based on meteorological conditions, crop and nozzle parameters - Calibrated using experimental data	Klein, 1995
PEDRIMO	- PEDRIMO: PEsticide DRIft MOdel - Screening model (sediment and loss to the air) for field, orchard and aerial sprayings - Assessment of weather conditions and technological parameters in its influence on drift - Presented in tables - Multiple linear regression of German drift values to estimate input into aquatic ecosystems - Describes a physical and statistical relation superposed by random effects - Based and validated with field experiments	Kaul *et al.*, 2004
SPRAYTRAN	- Geographic Information System (GIS)-based atmospheric dispersion model for estimating off-target drift of pesticides - Developed by U.S. Department of Agriculture, Forest Service and U.S. Environmental Protection Agency (EPA) - Treats with transport distances from a several up to hundreds of kilometres	

2.5. International drift regulations

An overview about different international drift regulations has been given by van de Zande (2002).

2.5.1. United Kingdom - LERAP

Buffer zones have been used in the UK since 1990 to protect aquatic life from spray drift. Initially, a standard distance of 6 m (from sprayed area to water surface) is used where application is done by boom sprayers. This length was intended to represent the length of a typical spray boom section, which could be turned off during application in order to comply with a buffer zone. This distance now has been changed to 5 m from sprayed area to the top of the bank of a waterbody. A more flexible, practical and enforceable approach was needed and the Local Environment Risk Assessment for Pesticides (LERAP) scheme was developed (MAFF, 1999). The aim of the scheme was to allow flexibility in buffer zone widths with maintaining a high level of environmental protection. Factors incorporated in the scheme are: application rate (dose), waterbody size (width) and spray application technology. The data utilised are those produced by Ganzelmeier *et al*. (1995). New technology in spray applications offers benefits in terms of reduced drift. An accreditation system based on independently assessed data on the performance of sprayers was set up. This system classifies spray drift reduction and is expressed as LERAP-Low Drift Star Ratings. This system awards star rating by comparing the level of drift from candidate systems with the drift level from the reference system.

The reference system is defined as an open-structured boom structure fitted with ISO 03 standard flat fan nozzles at a pressure of 3 bar manufactured from stainless steel and operating at a nozzle height of 0.5 m above the target. Star rating may be allocated based on the criteria defined in Table 2.15. The spray drift fallout deposition profile from the reference spraying system which is used to assess claims for LERAP-Low Drift status is calculated for a 12 m wide spray swath. This curve is based on original data collected by Glass *et al*. (1998 b).

Table 2.15: Definition of LERAP-Low Drift Star Ratings (Gilbert, 2000)

LERAP-Low Drift Rating	Drift performance (measurable as ground deposition of spray drift)
None	Drift levels > 75% of that from reference system
*	Drift levels > 50% and < 75% of that from reference system
**	Drift levels > 25% and < 50% of that from reference system
***	Drift levels < 25% of that from reference system

The LERAP system separates pesticide products that have a requirement for a buffer zone into two categories. Category A includes products which are not included in the LERAP scheme and hence, their required buffer zone cannot be reduced. Category B includes products for which LERAP does apply. For these products, users must conduct and record a LERAP assessment and may then reduce the buffer zone width. A summary of the unsprayed buffer zone width, based on the size of the watercourse, the LERAP star rating, and the applied dose is given in Table 2.16.

Table 2.16: Summary of LERAP buffer zone reduction options (Gilbert, 2000)

Watercourse width (m)	Buffer zone (m) needed for reference, *, ** and *** LERAP star-rated sprayers			
	Full dose	¾ dose	½ dose	¼ dose
< 3	5, 4, 2, 1	4, 2, 2, 1	2, 1, 1, 1	1, 1, 1, 1
3 - 6	3, 2, 1, 1	2, 1, 1, 1	1, 1, 1, 1	1, 1, 1, 1
> 6	2, 1, 1, 1	2, 1, 1, 1	1, 1, 1, 1	1, 1, 1, 1

2.5.2. The Netherlands

As reported by van de Zande (2002), the width of buffer zones in The Netherlands is determined based on reference drift curves to minimize risk to the aquatic system in surface water. Standardised ditch dimensions are 1.5 m bank-length on both sides of a surface water width of 1 m. The minimal distance from the last nozzle to the surface water varies depending on the crop type and the spray application techniques. Crop free buffer zones, to be implemented from the year 2000 onwards following the Water Pollution Act (V&W/VROM/LNV, 2000), with the accompanying distances from the last nozzle to the surface water area are shown in Table 2.17 using low-drift nozzles.

Table 2.17: Crop-free buffer zones and distance of the last nozzle to the surface water as implemented from the year 2000 onwards (Water Pollution Act), for a conventional and an air-assisted sprayer using low-drift nozzles

Crop type	Crop free buffer zone (m)		Distance last nozzle to surface water (m)	
	Conventional	Air-assisted	Conventional	Air-assisted
Potatoes	1.50	1.0	2.875	2.375
Sugar beets	0.50	0.50	2.25	2.25
Cereals	0.25	0.25	2.0	2.0
Flower bulbs	1.50	1.0	2.75	2.25

In the Water Pollution Act, packages of drift measurements are described to be implemented on the outside 14 m of the fields by Dutch farmers. A minimum drift-reducing package for arable farming is the use of low drift nozzles, a sprayer boom height of 0.5 m and an end-nozzle. Buffer zone width can be reduced to 1.0 m with the additional use of air assistance on the sprayer or planting a drift-collecting crop on the field boundary. A low-drift nozzle is defined as a nozzle potentially reducing drift with at least 50% compared with the fine/medium threshold nozzle from the BCPC nozzle classification scheme as described in section 2.2.1.4. Low-drift nozzles can be certified and listed based on drop size measurements when the volume fraction of drops smaller than 100 µm is less than 50 % of the BCPC fine/medium threshold nozzle.

2.5.3. Germany

Buffer zones have been set in Germany as label restrictions since 1988. For products with a high toxicity, buffer zones of 20 m were specified for arable crops and up to 50 m for tall growing crops. At this stage, buffer zones have mainly been set based on one standard use situation that represented a reasonable worst case. The exposure assessment was based on the maximum application rate and the German drift values (Ganzelmeier *et al.*, 1995).

Later on, a more differentiated scheme has been set up based on risk mitigation measures (Streloke & Winkler, 2001) and new drift values have been published (Ganzelmeier & Rautmann, 2000). A new official list of drift-reducing techniques has been published (BBA, 2000 a) in which additional use situations are considered which may lead to another risk to the aquatic organisms than the standard one. The different conditions influencing the risk are: the application rate, the spray application technology, the type of waterbody, vegetation on the embankment, bio-availability of compounds, recovery and recolonization potential in the waterbody and the sensitivity of the affected community. Considering all these arguments, four different risk categories were identified. Each risk category having a fixed degree of risk reduction compared to the standard situation. These categories A, B, C and D represent reductions of 99, 90, 75 and 50% and specify risk-points to be gained as specified in Table 2.18.

Table 2.18: Risk category, degree of risk mitigation, risk points and typical use conditions (Streloke & Winkler, 2001)

Risk Category	Risk mitigation (%)	Risk points	Local use conditions
A	99	20	No entry up till now
B	90	10	Application technique with 90% drift reduction
C	75	6	Application technique with 75% drift reduction
C	75	6	Lotic waterbodies with a minimum width of 2 m
D	50	3	Application technique with 50% drift reduction
D	50	3	Riparian vegetation with a minimum width of 1 m

Depending on the exotoxicological risk of the plant protection product the label gives information on the basic width of the buffer zone and on the reduction in buffer zone width for the different risk categories. These distances are specified in official published documents (Anonymous, 2000). The risk points can be added up when risk mitigation measures are combined. For example, a 75% drift-reducing technique (6 points) alongside a streaming waterbody of at least 2 m width (6 points) adds up to 12 points and is therefore classified in category B.

Today, nearly all products on the market in Germany are labelled with buffer zone restrictions. Maps have been made of rivers and their tributaries so that, by using a GIS-based decision support system with a graphical user interface, a farmer can determine where he or she can treat their fields without infringing the regulations to protect water (Ropke *et al*., 2004; Ganzelmeier, 2005).

2.5.4. Sweden

In Sweden, required buffer zone widths are summarised in tables (Anonymous, 1999) and are given for different temperature and wind speed, spray quality, field size, spray technique (boom height), application rate and the type of area (sensitive or normal). Examples of sensitive areas are water, gardens, greenhouses, organic farming, schools and crops sensitive to the used pesticides that are grown next to the treated field. For the sensitive areas, the buffer zones are calculated to give a maximum of 1% of the highest recommended dose for the pesticide used based on the highest amount of Deltametrin that can be allowed in surface water without causing environmental damage. A normal area means that the surroundings next to the field need to be protected but that it is not especially sensitive for the pesticide. In these areas, drift may be maximally 4% of the highest dose for the pesticide. The effect of accumulated drift on a certain spot outside the field from additional spray swathes is dealt with in a field size factor. The effect of dose is incorporated in the choice between full, half and quarter dose. Also the effect of spray application technology is incorporated in a boom height factor. Spray quality is brought into account according to the BCPC spray quality categories. An example is given in Table 2.19.

Table 2.19: An example of the effect of spray quality, dose and environmental conditions (temperature and wind speed) on advised unsprayed buffer zone width in Sweden for two types of sensitive areas when spraying wide field (> 96 m) with a boom height of 0.60 m (Anonymous, 1999)

Wind speed ($m.s^{-1}$)	Sensitive area	Buffer zone (m) needed for coarse, medium and fine BCPC Spray quality								
		Temperature 10°C			Temperature 15°C			Temperature 20°C		
		Full dose	½ dose	¼ dose	Full dose	½ dose	¼ dose	Full dose	½ dose	¼ dose
1.5	Normal	2, 3, 5	2, 2, 2	2, 2, 2	2, 4, 6	2, 2, 2	2, 2, 2	3, 5, 7	2, 2, 2	2, 2, 2
	Sensitive	9, 20, 34	3, 8, 12	3, 3, 3	14, 28, 42	5, 10, 16	3, 4, 6	20, 34, 50	7, 12, 18	3, 4, 7
3.0	Normal	2, 3, 5	2, 2, 2	2, 2, 2	3, 6, 8	2, 2, 3	2, 2, 2	6, 8, 11	2, 3, 4	2, 2, 2
	Sensitive	12, 24, 38	4, 9, 14	3, 3, 5	36, 38, 50	9, 16, 22	3, 5, 8	44,>50,>50	16, 22, 28	6, 8, 11
4.5	Normal	2, 4, 6	2, 2, 2	2, 2, 2	5, 7, 10	2, 3, 4	2, 2, 2	9, 12, 15	3, 4, 5	2, 2, 2
	Sensitive	16, 30, 44	6, 11, 16	3, 4, 6	38,>50,>50	14, 20, 28	5, 7, 10	>50,>50, >50	14, 32, 38	9, 11, 14

2.5.5. Belgium

In Belgium, a buffer zone regulation has been introduced since 2005 following a preparatory study of Huygebaert *et al.* (2004). In this regulation, a buffer zone is defined as an unsprayed zone along a watercourse. Buffer zone widths are mentioned on the product label and are determined based on the toxicity of the product and the drift data produced by Ganzelmeier *et al*. (1995). Using a drift reducing spray application technique, this buffer zone width can be reduced as presented in Table 2.20.

For field sprayers, spray application techniques are subdivided into four classes (standard, 50, 75 and 90% drift reduction). The drift reduction class is determined based on the nozzle type, nozzle size and the type of sprayer (standard spray boom, air support, shielded spray boom, etc.). Note that spray pressure is not brought into account. The reference system is defined as a standard spray boom fitted with ISO 03 standard flat fan nozzles at a pressure of 3.0 bar. A complete list of classified drift reducing spray application techniques in Belgium is available on www.phytoweb.fgov.be. For orchard sprayers, a comparable system is available but for this type of sprayings, the presence of a hedge also influences the drift reduction class.

Table 2.20: Belgian buffer zone widths to be respected with field sprayers as a function of spray application technique and label recommendations (www.phytoweb.fgov.be)

Spray application technique	Buffer zone on the label						
	2 m	**5 m**	**10 m**	**20 m**	**20 m with 50% drift reducing technique**	**20 m with 75% drift reducing technique**	**20 m with 90% drift reducing technique**
	with standard application technique						
Standard	2 m	5 m	10 m	20 m	30 m	40 m	200 m
50% drift reduction	1 m	2 m	5 m	10 m	20 m	30 m	40 m
75% drift reduction	1 m	2 m	2 m	5 m	10 m	20 m	30 m
90% drift reduction	1 m	1 m	1 m	1 m	5 m	10 m	20 m

2.5.6. Other countries

The Australian Pesticides & Veterinary Medicines Authority calculates no-spray zones with risk factors (wind speed, droplet size, etc.) set at higher levels of risk likely to occur in real applications. However, sometimes risks are lower, for example when the wind is light or when a coarser droplet range is used. The Canadian proposal (Pest Management Regulatory Agency, PMRA) is designed to accommodate lower risk factors for specific applications by allowing the use of a multiplier defined for each situation so that applicators can reduce the prescribed buffer zone by the value of the multiplier that applies to the situation they are facing (Kuchnicki *et al*., 2004).

Chapter 3 PDPA laser-based spray droplet characterisation

3.1. Introduction

The spray quality generated by agricultural nozzles is important considering the efficiency of the pesticide application process because it affects spray deposits and driftability (Taylor *et al*., 2004). Further, spray quality influences biological efficacy of the applied pesticide as well as environmental hazard (Permin *et al*., 1992; Klein & Johnson, 2002; Wolf, 2002). The ideal nozzle-pressure combination should maximize spray efficiency by increasing deposition and transfer of a lethal dose to the target, while minimizing off-target losses such as spray drift and user exposure. The spray characteristics influencing the efficiency of the pesticide application process are the droplet size and velocity distribution, the volume distribution pattern, the entrained air characteristics, the spray sheet structure and the structure of individual droplets (Miller & Butler Ellis, 2000). This work focuses on the droplet size and velocity characteristics.

Over recent years, several techniques using laser instrumentation have been developed to determine droplet characteristics, such as laser diffraction (e.g. Malvern laser) (Barnett & Matthews, 1992; Butler Ellis & Bradley, 2002), the optical area probe technique (e.g. Particle Measuring System) (Combellack *et al*., 2002) and the phase doppler particle analyzer (PDPA, e.g. Aerometrics) (Farooq *et al*., 2001 a; b). These techniques are described in detail in section 2.3.2.

Each instrument type has different measuring characteristics. The Malvern uses a spatial measuring technique, is not capable of measuring velocities and determines a spatially averaged size distribution. The PDPA relies like the optical area probe technique on single droplet measurement. As for the PDPA, a droplet passes through a small sampling volume, scattering light by refraction. The frequency of this light being proportional to droplet velocity and the spatial frequency of the same light inversely proportional to the droplet diameter (Bachalo & Houser, 1984). This results in a temporal-averaged measurement of the spray. Arnold (1987) showed that droplet velocity influenced droplet measurement due to the resident time of in-flight droplets in the laser measuring volume. Hewitt and Valcore (1995) measured similar droplet sizes between a Malvern and a PDPA instrument when a 37 $km.h^{-1}$ airstream was applied to the droplets measured with the Malvern. Theoretically, this airstream equalized the velocity of droplets of different size thereby resulting in similar droplet resident times for the Malvern's number density weighted measuring system.
The optical area probe technique allows size and velocity to be determined of individual droplets passing through a small measuring volume. Generally, the Particle Measuring System instrument measured a significantly greater volume median diameter compared to the Malvern, except for very low flow rates (Arnold, 1987). The PDPA gave consistently lower values for the volume median diameter and lower percentages of spray volume in

droplets less than 100 μm in diameter than the PMS (Tuck *et al*., 1997). Besides different measuring techniques, there are important differences between different researches in measuring set-up and protocol (e.g. nozzle height, scan pattern, sampling strategy, data processing, etc.) which have an effect on the measuring results (Chapple & Hall, 1993; Butler Ellis *et al*., 1997).

Because of differences in measuring technique, set-up and protocol, different researches have shown a wide variation in mean droplet sizes for the same nozzle specifications (Western *et al*., 1989 [Particle Measuring System]; Barnett and Matthews, 1992 [Malvern]; Miller *et al*., 1995 b [Dantec PDPA]; Tuck *et al*., 1997 [Dantec PDPA & Particle Measuring System]; Hewitt *et al*. 1998 [Malvern]; Porskamp *et al*., 1999 [Aerometrics PDPA]; Womac *et al*., 1999 [Malvern]; Nilars *et al*., 2000 [Aerometrics PDPA & Particle Measuring System]; Womac, 2000 [Malvern]; Herbst, 2001 a [Aerometrics PDPA, Malvern & Oxford Laser]; Powell *et al*., 2002 [Oxford Laser]; Butler Ellis and Bradley, 2002 [Malvern] and van de Zande *et al*., 2002 b [Aerometrics PDPA]). Moreover, some researchers did not use reference nozzles (Western *et al*., 1989; Barnett & Matthews, 1992). Young and Bachalo (1987) investigated differences in measurements of droplet size between all three laser techniques and found that comparative data can be obtained when measuring reference sprays. However, they found that agreement between instruments deteriorates for coarse agricultural sprays. That is why efforts are made to define an international standard for the measurement and classification of droplet size spectra from atomizers using reference sprays (ISO/CD 25358, 2007) .

The main objective of this chapter was to measure and compare droplet size and velocity characteristics of different nozzle-pressure combinations including the BCPC reference nozzles. The sub-objectives to obtain this main objective were as follows:

- To develop a measuring set-up and establish a detailed measuring protocol using a PDPA laser for droplet characterisation of agricultural spray nozzles,
- To compare the measuring results with the results obtained by other researchers using different measuring techniques and procedures.

In Chapter 6, the droplet characteristics will be linked to the drift potential of the different nozzle-pressure combinations obtained from wind tunnel (Chapter 4) and field drift experiments (Chapter 5). The measuring results were used as an input for a computational fluid dynamics drift-prediction model (Baetens *et al*., 2006; 2007 a). The results of this chapter were published in Nuyttens *et al.* (2005 a & d; 2006 a & b; 2007 b & d).

3.2. Materials and Methods

The measuring set-up developed and used in this research is composed of a controlled climate room (§ 3.2.1), a spray unit (§ 3.2.2), a three-dimensional automated positioning system (§ 3.2.3) and an Aerometrics PDPA laser system.

3.2.1. Climate room

The laser measurements are performed in an insulated controlled climate room (inside dimensions: 8 m length, 3.70 m width, 3.37 m height) equipped with temperature and humidity control. Temperature control is accomplished by two cooling and heating units. Freon R407C is used as a refrigerant and the total cooling capacity is 12.82 kW. These units are also used to dehumidify together with a Condair CP D8 humidifier. Under normal working conditions, a temperature range from 5 to 30°C and a relative humidity range from 30 to 90% are achievable. Hence, different realistic outdoor climatic conditions can be simulated.

3.2.2. Three-dimensional positioning system

When measuring droplet characteristics, the PDPA measurements are made at a fixed point and the nozzle can be moved using an automated XYZ-transporter with a traverse range of 2.0 m by 2.2 m (Figure 3.1). The XY-movement is achieved using two Siemens Simodrive Posmo A motors controlled by a Siemens Programmable Logic Controller (PLC) with a control panel. These motors have a rating of 300 W and are equipped with a 1/49 reducer to optimise the accuracy of the positioning system.
The vertical distance between the nozzle and the measuring point (Z-direction) can be adjusted manually from 0 to 0.90 m. The measuring point is located at a height of 0.80 m above the floor to avoid measurement errors due to rebounding droplets.

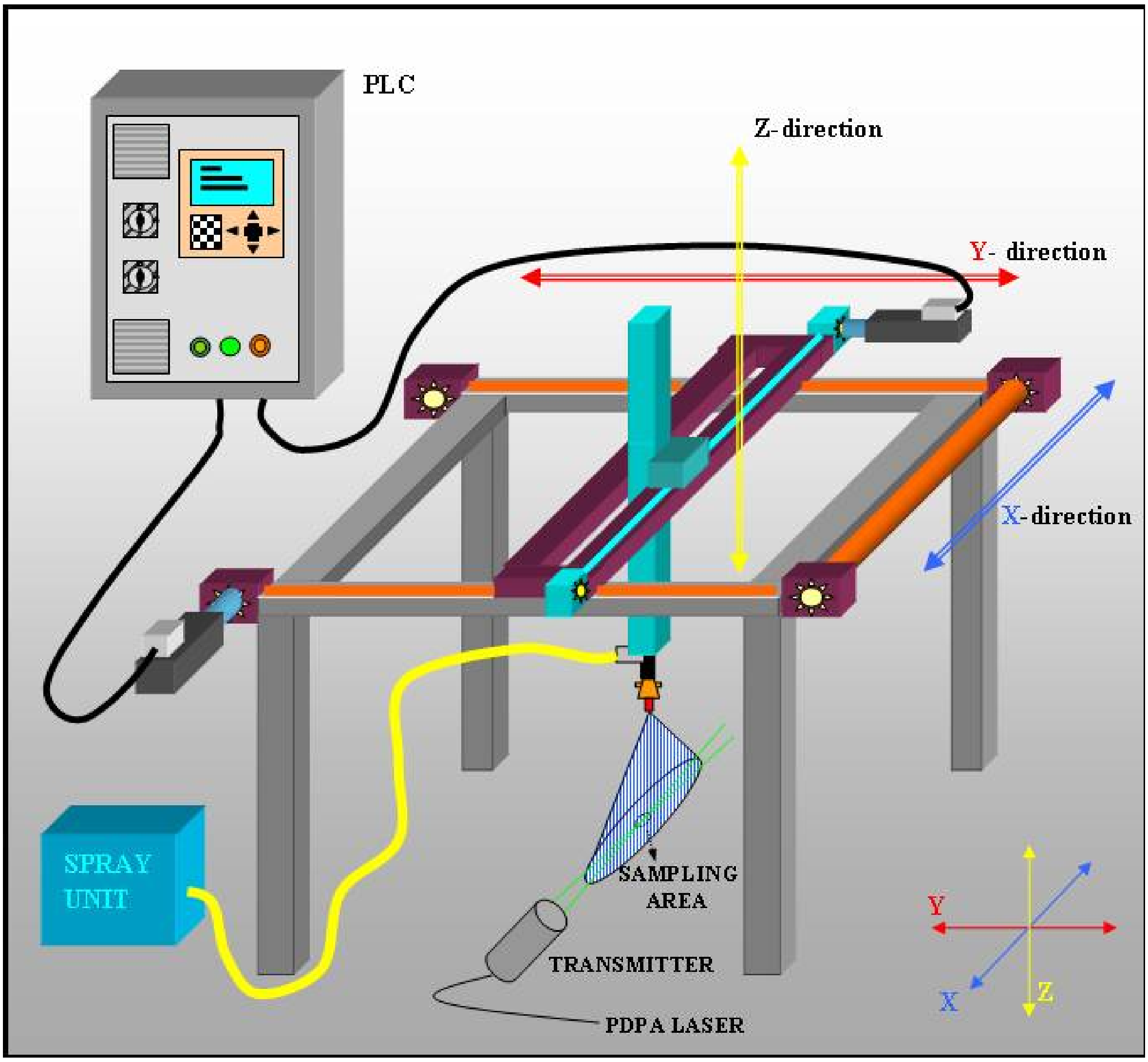

Figure 3.1: Schematic overview of the automated XYZ-transporter with the intersecting laser beams and sampling area

Different scan patterns can be carried out, each with the start and end position of the spray nozzle in the centre of the XY-rectangle straight above the measuring point. The possible scan patterns are:

- a free manually-controlled movement of the spray nozzle,
- a movement of the spray nozzle to a certain XY position in which the nozzle is stationary for a definable period of time,
- a scanning of a defined rectangular pattern to effect a 'complete' scan of the spray cloud.

In case of scanning a rectangular pattern the length of the rectangular scan pattern x (m), the distance interval in the X direction during scanning Δx (m), the width of the rectangular scan pattern y (m) and the distance interval in the Y direction during scanning Δy (m), can be chosen as illustrated in Figure 3.2. There are two possible ways of scanning: (a) continuous, at a constant definable scanning speed v_s (m.s^{-1}) without stops and (b) discontinuous, with stops at distance intervals Δx for a definable period of time.

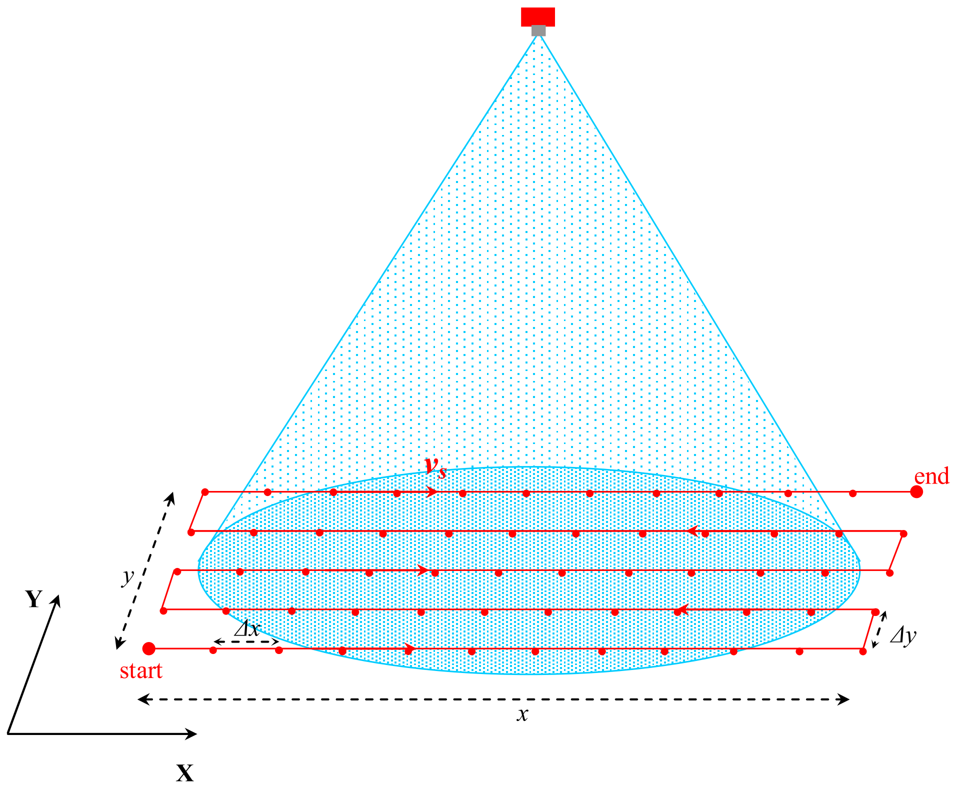

Figure 3.2 : Scan trajectory; x and y, length and width of the rectangular scan pattern; Δx and Δy, distance intervals in the X and Y direction; v_s, scanning speed

3.2.3. Spray unit

The spray unit consists of the following parts as presented in Figure 3.3, namely:

- A 100 litre insulated spray liquid tank with a fluid level control system that can be switched off if an active ingredient is used.
- A liquid temperature control system with a Pt100 temperature sensor at the exit of the liquid tank, just before the spray nozzle; a PID regulation system, a heating resistor (with a capacity of 6 kW), a water cooling unit, and a mechanical as well

as a hydraulic mixing of the tank contents. In case of continuous spraying, a fluid temperature range from 5 to 50°C was feasible.

- A vertical in-line centrifugal pump with a maximum power of 1.5 kW at 2850 revolutions per minute that can deliver 1.4 $L.s^{-1}$ at a pressure of 6.6 bar with a maximum capacity of 5 $m^3.h^{-1}$.
- A manually adjustable pressure regulator and a digital pressure gauge with a resolution of 0.01 bar.

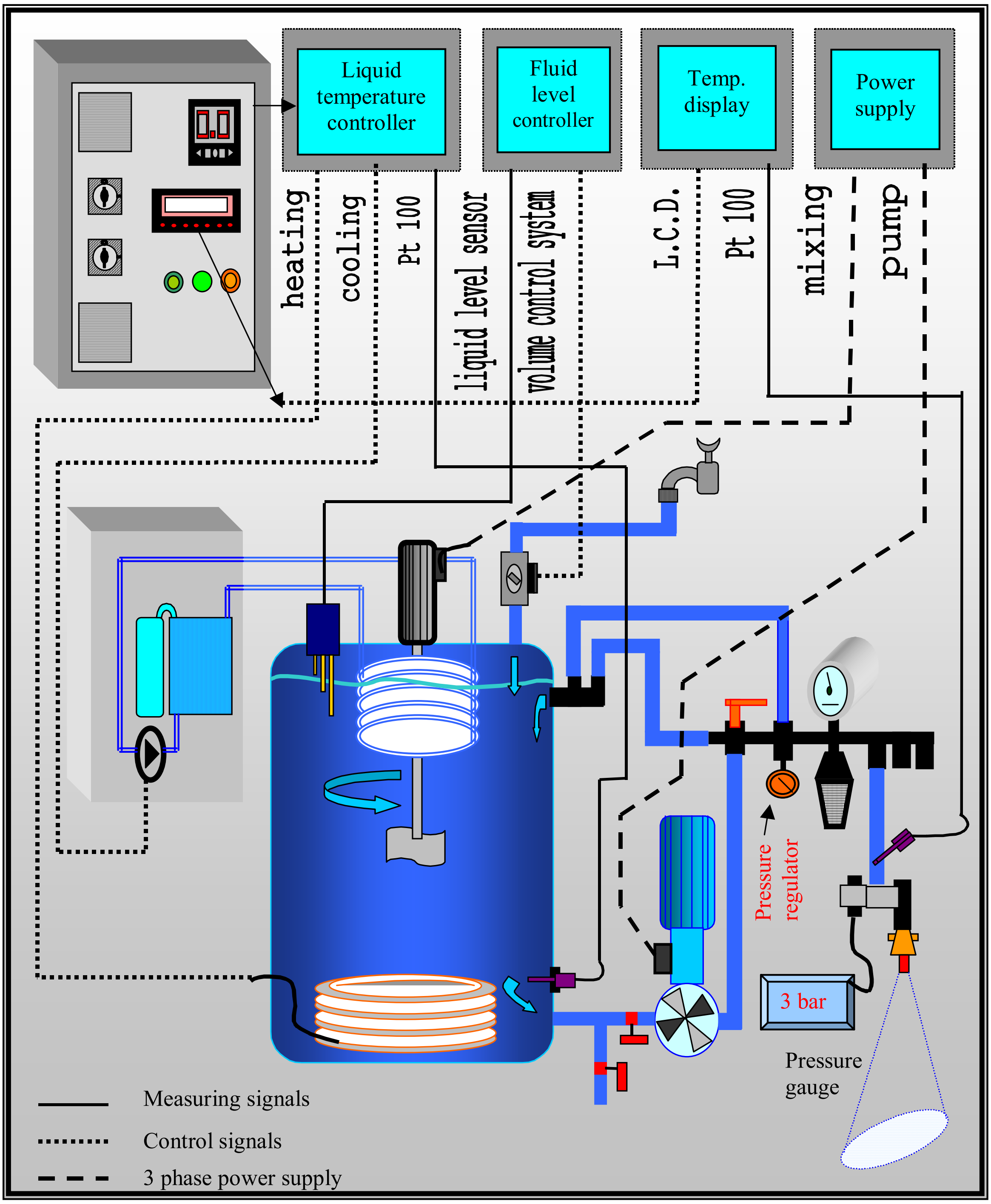

Figure 3.3 : Schematic overview of the spray unit

3.2.4. Aerometrics Phase Doppler Particle Analyser

The PDPA laser used in this research was an Aerometrics PDPA 1D (TSI, Minneapolis). The system comprises several components, namely: an Argon-Ion laser, a fibre drive, a fibre-optic coupler, a fibre-optic transmitter and receiver, a real-time signal Analyzer (RSA), and DataVIEW-NT 2.0.4.0 software (Figure 3.4). With this apparatus, droplets pass through a small sampling volume, scattering light by refraction. Velocity measurement with the one-dimensional system used, is limited to the dominant vertical direction.

The 300 mW Argon-Ion laser produces green laser light with a constant wavelength of 514.5 nm. The fibre drive, which is an optical instrument, accepts and manipulates the laser beam before coupling and launching it into the optical fibres for transmission. An acousto-optic modulator (Bragg cell) splits the incoming beam into two beams of equal intensity. The first beam is shifted in frequency by 40 MHz. Two colour dispersion prisms separate the beam chromatically and separate the green beam. A beam separation prism directs the two beams towards opposite sides of the fibre drive. After passing some mirrors, the beams exit the fibre drive and are coupled into an optical fibre by a fibre-optic coupler. This fibre-optic coupler receives, steers, and focuses the beams onto the face of an optical fibre for transmission to the transmitter.

By means of the fibre-optic transmitter the beams are focused to cross over at a distance equal to the focal length (500 mm) of the transmitter lens. The sampling area is formed by the intersecting beams and has the shape of an ellipsoid. Beam separation, beam diameters and focal length alter the angle at which beams interfere thereby determining the detectable size and velocity ranges. Other parameters influencing measurement ranges are the laser wavelength, settings of the receiving optics and the signal processor band (Tuck *et al*., 1997). For the optical configuration in this study, the ellipsoid is 46.8 mm by 0.468 mm (Annex 1). The intersection of the two beams creates a fringe pattern within the sampling area. The number of fringe spaces for our optical set-up was 18 (see Annex 1). The fringe spacing δ_f (m) between the interference fringes can be calculated by the laser wavelength λ (m) and the angle between the two laser beams θ (°) as follows:

$$\delta_f = \frac{\lambda}{2.\sin(\frac{\theta}{2})} \qquad (3.1)$$

This results in a fringe spacing δ_f of 25.7 µm when λ is 514.5 nm and θ is 1.146°, derived from an initial beam spacing of 0.01 m and a focal length of 0.50 m. Hence, the fringe spacing depends on the beam intersection angle. When a spherical particle crosses the intersection of both laser beams, the rays enter the sphere at different angles. Since the particle has a different index of refraction than the surroundings, the rays have to travel along different optical paths with different lengths. Because of the different optical path lengths, the lightwaves are shifted relative to each other. These phase shifts result in an interference pattern in the field surrounding the particle (Bachalo & Houser, 1984). Interference fringes are bright and dark lines produced by the constructive and destructive interference of the intersecting lightwaves. If a droplet is moving with a velocity v_d (m.s^{-1}) through the intersection of the beams, light will scatter with a frequency f_d (s^{-1}). This frequency f_d is equal to the droplet velocity v_d (m.s^{-1}) divided by the fringe spacing δ_f (m).

Hence, frequency and particle velocity are related as follows:

$$v_d = f_d.\delta_f = f_d.\frac{\lambda}{2.\sin(\frac{\theta}{2})} \qquad (3.2)$$

The fibre-optic receiver collects the scattered laser light. The instrument was operated in the near-forward scatter mode (first order of refraction) with the receiving optics set at 30° to the incident beam (Tuck *et al.*, 1997). This produces the highest sizing sensitivity and the most satisfactory results for transparent liquids like water. The fibre-optic receiver consists of two lenses with focal lengths of 300 mm (front lens) and 250 mm (back lens). The receiver lens system focuses the light onto a spatial filter to limit the extent of the sampling area. Light passing through the slit (slit aperture: 100 µm) is collimated by the collimating lens onto the mask. The mask effectively partitions the receiver lens into four regions. These regions become the three detectors used by the PDPA to determine size and velocity. After passing through the mask, light is directed by the prism pack to the three photomultiplier tubes (PMT's) which convert the light signals (photons) into electrical signals (electrons) by the photoelectric effect. These voltage signals are processed for velocity and size information by the real-time signal analyzer 3100-P (RSA).

The RSA is designed for real-time processing of laser Doppler velocimeter and phase Doppler signals based on the discrete Fourier transform method. Signals are detected, processed and validated simultaneously and continuously. Each PMT produces a signal with a frequency proportional to the particle velocity. The phase shift between the signals from two different PMT's is proportional to the size of the spherical particles (Bachalo & Houser, 1984; Borys, 1996).
Finally, DataVIEW-NT 2.0.4.0 software contributes to the overall ease of use of the system and gives complete control over the presentation and acquisition of the data.

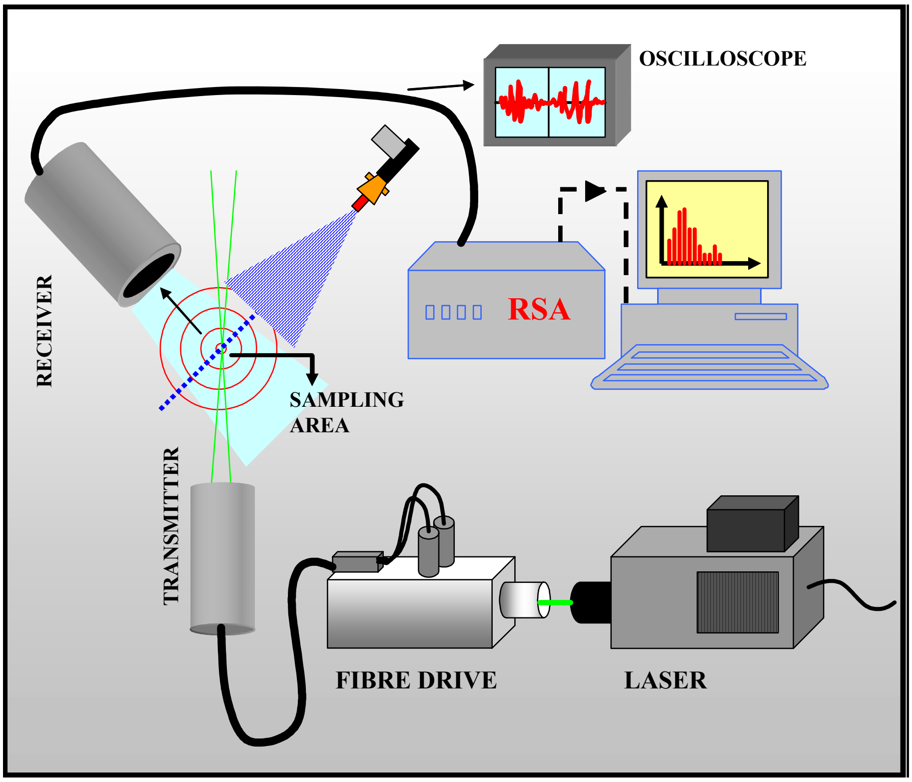

Figure 3.4: Schematic overview of the PDPA optical laser instrument

Measurement ranges for velocity and diameter can be changed through variations in the optical equipment, laser beam separation, and lens focal lengths of the transmitting and receiving optics. Settings on the instrument were chosen to cover a size range of 9 to 1000 µm, corresponding respectively with phase shifts of 3° to 350°.

Phase doppler particle analyser systems sometimes have a tendency to generate erroneous measurements for larger droplets and so can have an adverse effect on spray quality estimates. This is caused by laser reflection instead of refraction leading to a faulty interpretation by the system. Another possible reason is the passing of more than one droplet at a time through the measuring volume. As these erroneous data generally refer to large droplets, they can have an important influence on the droplet size characteristics of a spray. For this reason, validation criteria are used to decide whether a droplet is to be accepted or discarded. These erroneous measurements are eliminated by analysing a graph of the intensity versus the diameter. Upper and lower limit curves determine which droplets to accept and which to discard. A big droplet with low intensity is often a cause of the above-mentioned error, and since a big droplet is expected to refract light with large intensity, it is discarded from the measurement. The same is valid for small droplets with a high intensity. Elimination of operator dependency is by no means complete and this can lead to differences between laboratories. However, a certain degree of data evaluation is possible using this intensity validation feature.

The PDPA instrument requires no calibration because the droplet size and velocity are dependent only on the laser wavelength and optical configuration. PDPA measurements are not based upon the scattered light intensity and, consequently, are not subject to errors from beam attenuation or deflection which occur in dense particle environments. This type of measuring equipment has already been used among others by Bachalo and Houser (1984), Matthews (1992), Wolf *et al*. (1995), Lund and Matzen (1996), Downer *et al*. (1997), Sidahmed *et al*. (1999) and Butler Ellis and Tuck (1999). Figure 3.5 shows some pictures of the full measuring set-up.

Figure 3.5: Some pictures of the PDPA laser measuring set-up

3.2.5. Measuring Protocol

Before any PDPA laser measurements, the flow rate of each nozzle was tested at a pressure of 3.0 bar by the accredited Spray Technology Laboratory (BELAC, 2006; BELAC accreditation certificate No. 197 - Test according NBN EN ISO/IEC 259 17025:2000) of the Institute for Agricultural and Fisheries Research (ILVO) (Goossens & Braekman, 2003). A maximal deviation of ± 2.5% was allowed compared to the prescribed nominal flow rate.

For the PDPA measurements in this research, three nozzles were selected for each nozzle-pressure combination as described in section 3.3.1 and each nozzle was tested three times. This makes a total of 9 measurements for each nozzle-pressure combination carried out in random order. Each scan yielded data for at least 10 000 droplets as recommended by Adams *et al*. (1990) and Tuck *et al*. (1997). The British Crop Protection Council (BCPC) reference nozzle fine-medium (Lurmark F 110 03 at 3.0 bar - stainless steel) was used as a reference nozzle to check for the repeatability of the measuring equipment before and after each measuring session (Southcombe *et al*., 1997). All measurements were made spraying water at a temperature of approximately 20°C. Environmental conditions were kept constant at a temperature of 20°C and a relative humidity between 60 and 70% because of the important influence of environmental conditions on spray formation as described in section 2.2.4. The nozzle was positioned 0.50 m above the measuring point of the PDPA.

To enable the whole of the spray fan to be sampled, the nozzle was mounted on the transporter because neither a single position nor a one-dimensional scan is necessarily representative of the whole spray from a flat fan nozzle (Butler Ellis *et al*., 1997; Lund & Matzen, 1996; Chapple & Hall, 1993). In general, a different scan trajectory (Figure 3.2) was programmed depending on the type of nozzle, i.e. 110° flat fan nozzle, 80° flat fan nozzle or 80° cone nozzle (Table 3.1). In this research, all nozzles under investigation were 110° flat fan nozzles and all measurements were carried out through the long axis of the spray cloud at a constant scan speed v_s of 0.0250 m.s^{-1} (Δx not applicable). Tuck *et al*. (1997) did not observe an effect of scan speed on the measuring results within a range from 0.001 to 0.05 m.s^{-1}. This measuring protocol agrees with the standard ASAE S572 “Spray nozzle classification by droplet spectra” and draft standard ISO/CD 25358 (2007) “International Standard: Equipment for crop protection - Measurement and Classification Procedure for Droplet Size Spectra from Atomizers”.

Table 3.1: Characteristics of the scan trajectory for the different nozzle types

	Scanning speed v_s (m.s^{-1})	x (m)	y (m)	Δy (m)	Measuring time (s)
110° flat fan nozzles	0.0250	1.50	0.40	0.10	316
80° flat fan nozzles	0.0166	1.00	0.40	0.10	324
80° cone nozzle	0.0300	1.00	1.00	0.10	400

x and y, length and width of the rectangular scan pattern; Δy, distance interval in the Y direction

3.2.6. Spray application techniques

In total, 18 nozzle-pressure combinations (162 measurements) were tested i.e. the 5 BCPC reference nozzle-pressure combinations (Southcombe *et al.*, 1997; § 2.2.1.4) and 13 Hardi nozzle-pressure combinations including the reference nozzle-pressure combination of this study which is the Hardi ISO F 110 03 at 3.0 bar. Besides this reference nozzle-pressure combination, different other nozzle types (standard flat fan, low-drift flat fan and air inclusion), nozzle sizes (ISO 02, 03, 04 and 06) and spray pressures (2.0 and 4.0 bar) were evaluated. An overview is presented in Table 3.2. These Hardi nozzle-pressure combinations will also be tested in the wind tunnel and in the field. Note that Hardi low-drift nozzles with an ISO 06 size are not on the market .

Table 3.2: Overview of the tested nozzle-pressure combinations

Nozzle	Pressure (bar)	Flow rate ($L.min^{-1}$)	Nozzle	Pressure (bar)	Flow rate ($L.min^{-1}$)
Delavan LF 110 01*	4.5	0.48	Hardi ISO F 110 04	3.0	1.60
Lurmark F 110 03*	3.0	1.18	Hardi ISO F 110 06	3.0	2.40
Lechler LU 120 06*	2.0	1.93	Hardi ISO LD 110 02	3.0	0.80
TeeJet 80 08*	2.5	2.88	Hardi ISO LD 110 03	3.0	1.20
TeeJet 80 15*	2.0	4.90	Hardi ISO LD 110 04	3.0	1.60
Hardi ISO F 110 02	3.0	0.80	Hardi ISO Injet 110 02	3.0	0.80
Hardi ISO F 110 03	2.0	0.98	Hardi ISO Injet 110 03	3.0	1.20
Hardi ISO F 110 03$	3.0	1.20	Hardi ISO Injet 110 04	3.0	1.60
Hardi ISO F 110 03	4.0	1.39	Hardi ISO Injet 110 06	3.0	2.40

* BCPC reference nozzle-pressure combinations; $ Reference nozzle pressure combination; F, Standard flat fan nozzles; LD, Low-drift flat fan nozzles; Injet, Air inclusion flat fan nozzle

3.3. Results and discussion

3.3.1. Accredited flow rate measurements

The three test nozzles for the PDPA laser measurements were selected based on flow rate measurements at a pressure of 3.0 bar carried out in the accredited Spray Technology Lab (BELAC 259 T ISO 17025). At least 5 different nozzles of the same type were tested. A maximal deviation of ± 2.5% was allowed compared to the prescribed nominal flow rate.

An overview of the flow rate measurements is presented in Annex 2 together with the selected nozzles for the PDPA laser measurements and the measuring conditions (water temperature, ambient temperature and relative humidity). For the same nozzle, the standard deviation between different flow rate measurements was negligible and hence, not presented in this table.

3.3.2. Droplet size characteristics

Besides the droplets size spectra, different droplet size characteristics are calculated:

- $D_{v0.1}$, $D_{v0.25}$, $D_{v0.75}$, $D_{v0.9}$ – volume diameter in µm below which smaller droplets constitute 10, 25, 75 and 90 % of the total spray volume,
- $D_{v0.5}$ – volume median diameter (*VMD*) in µm below which smaller droplets constitute 50% of the total volume,
- V_{50}, V_{75}, V_{100}, V_{150}, V_{200}, V_{250} – proportion of total volume in % of droplets smaller than 50, 75, 100, 150, 200 and 250 µm in diameter,
- D_{10}, D_{20}, D_{30} – arithmetic, surface and volume mean diameters in µm, given by:

$$D_{10} = \frac{\sum_{i=1}^{n} d_i}{n} \tag{3.3}$$

$$D_{20} = \sqrt{\frac{\sum_{i=1}^{n} d_i^2}{n}} \tag{3.4}$$

$$D_{30} = \sqrt[3]{\frac{\sum_{i=1}^{n} d_i^3}{n}} \tag{3.5}$$

  where d_i is the diameter in µm of droplet *i* and *n* is the total number of droplets,
- D_{32} – sauter mean diameter defined as the diameter in µm of a drop having the same volume to surface area ratio as the total volume of all the drops to the total surface area of all the drops, and given by:

$$D_{32} = \frac{\sum_{i=1}^{n} d_i^3}{\sum_{i=1}^{n} d_i^2} \tag{3.6}$$

- *NMD* – number median diameter in µm below which the droplet diameter for 50% of the number of drops are smaller,

- *RSF* – relative span factor, a dimensionless parameter indicative of the uniformity of the drop size distribution, defined as:

$$RSF = \frac{D_{v0.9} - D_{v0.1}}{D_{v0.5}} \qquad (3.7)$$

- *BCPC* – BCPC spray quality class based on droplet size characteristics $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$.

The BCPC reference nozzle-pressure combinations (Table 3.2) are used to define six spray quality classes, *viz.*: very fine (VF), fine (F), medium (M), coarse (C), very coarse (VC) and extremely coarse (EC). This classification is based on the comparison of the (cumulative) droplet size spectrum ($D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$) produced by a spray nozzle at a given pressure with these reference spectra. More information can be found in section 2.2.1.4. In Figure 3.6, the measured volumetric droplet size distribution is presented cumulatively for the five BCPC reference flat fan nozzle-pressure combinations for nozzle classification, i.e., Delavan LF 110 01 at 4.5 bar (very fine/fine), Lurmark F 110 03 at 3.0 bar (fine/medium), Lechler LU 120 06 at 2.0 bar (medium/coarse), TeeJet 80 08 at 2.5 bar (coarse/very coarse) and TeeJet 80 15 at 2.0 bar (very coarse/extremely coarse), together with the six corresponding spray quality classes (Southcombe *et al.*, 1997).

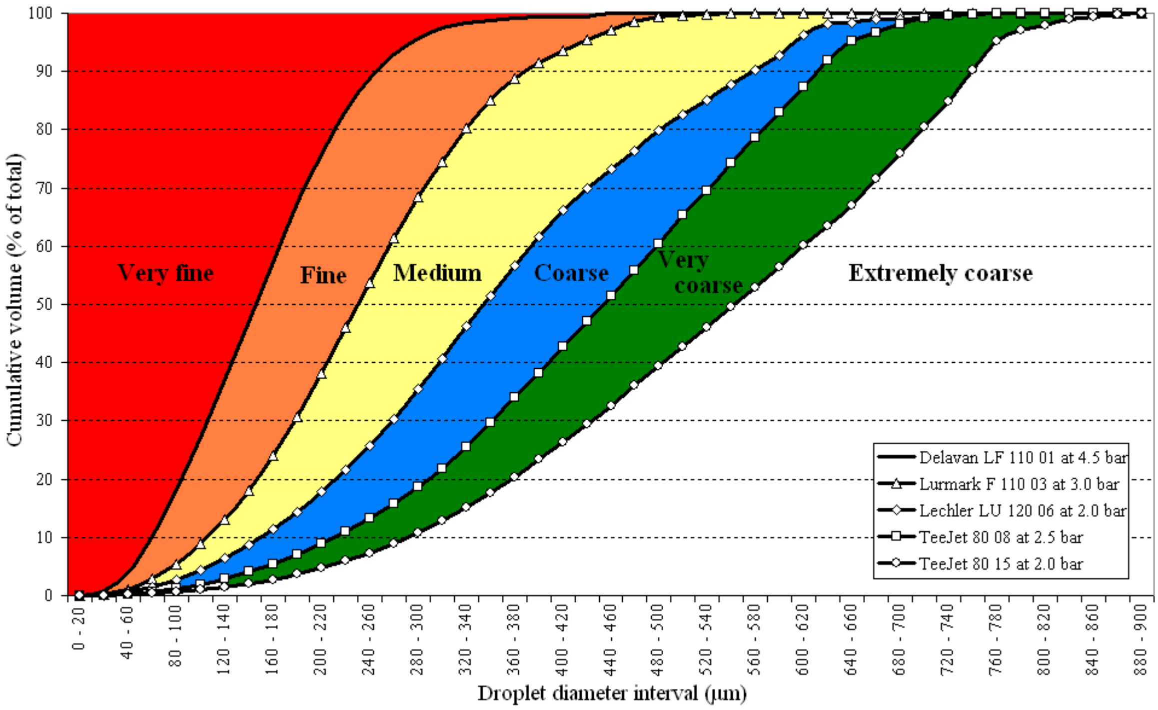

Figure 3.6: Cumulative volumetric droplet size distribution for the five BCPC reference nozzle-pressure combinations defining six spray quality classes (very fine, fine, medium, coarse, very coarse and extremely coarse)

Figure 3.7 presents the volumetric droplet size distribution for the different types (F, standard flat fan; LD, anti-drift flat fan; Injet, air inclusion) and sizes of Hardi agricultural spray nozzles at a spray pressure of 3.0 bar tested in this research (Table 3.2). The same results are presented cumulatively in Figure 3.8 for the same nozzles together with the five BCPC reference nozzle-pressure combinations. In Figure 3.9, droplet size characteristics $D_{v0.1}$, $D_{v0.25}$, $D_{v0.5}$, $D_{v0.75}$ and $D_{v0.9}$ for the Hardi nozzles at 3.0 bar and the BCPC reference nozzle-pressure combinations are presented together with the 95% confidence intervals for the reference nozzles, which are very small. In this chapter, confidence intervals are calculated using the t-distribution with a significance level α of 0.05 and eight degrees of freedom (df), corresponding with a critical t-value of 2.306. To test if the means of two normally distributed populations are equal or not, the t-test is used in this study.

Besides the BCPC reference nozzle-pressure combinations, other nozzle-pressure combinations show similar, very good repeatabilities. In general, droplet sizes vary from a few micrometres up to some hundreds of micrometres depending on the nozzle type and size. A complete overview of the different droplet size characteristics is given in Table 3.3 and Table 3.4. Average values and standard deviations based on nine repetitions are presented. Standard deviations are small, again indicating a very high repeatability of the measurements. As expected, the five BCPC reference nozzles cover the entire range of measured droplet sizes (Figure 3.8) and the majority of tested Hardi nozzle-pressure combinations is classified as medium.

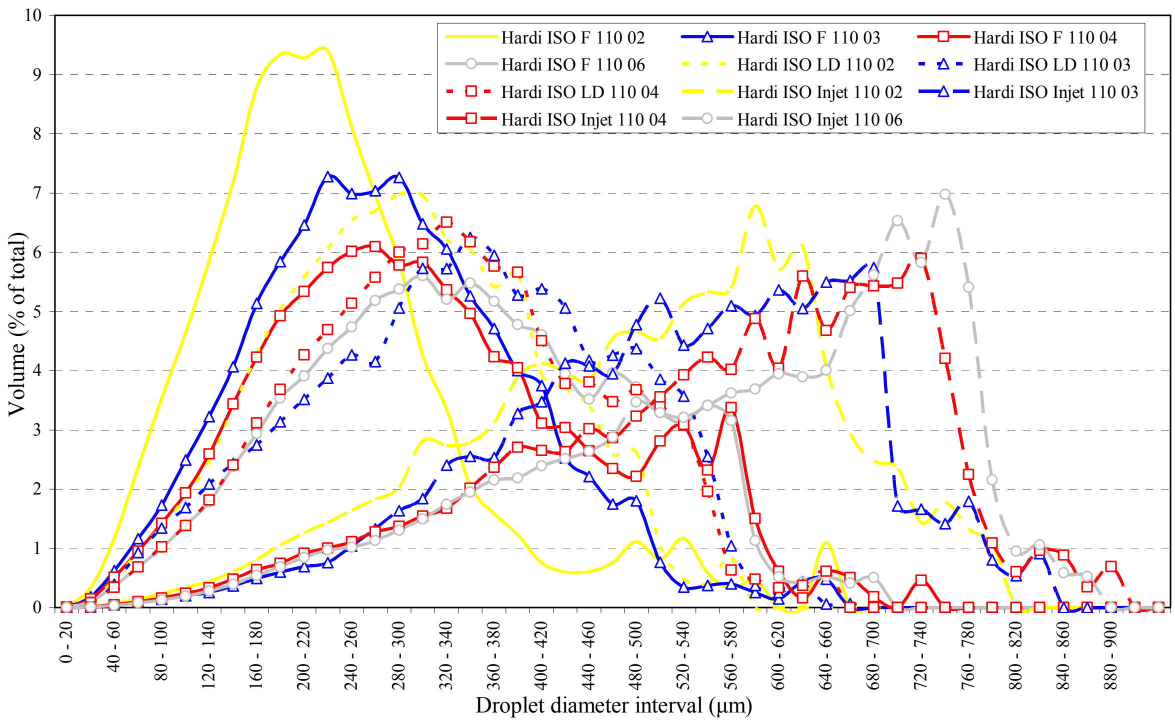

Figure 3.7: Volumetric droplet size distribution for different Hardi nozzles at a pressure of 3.0 bar

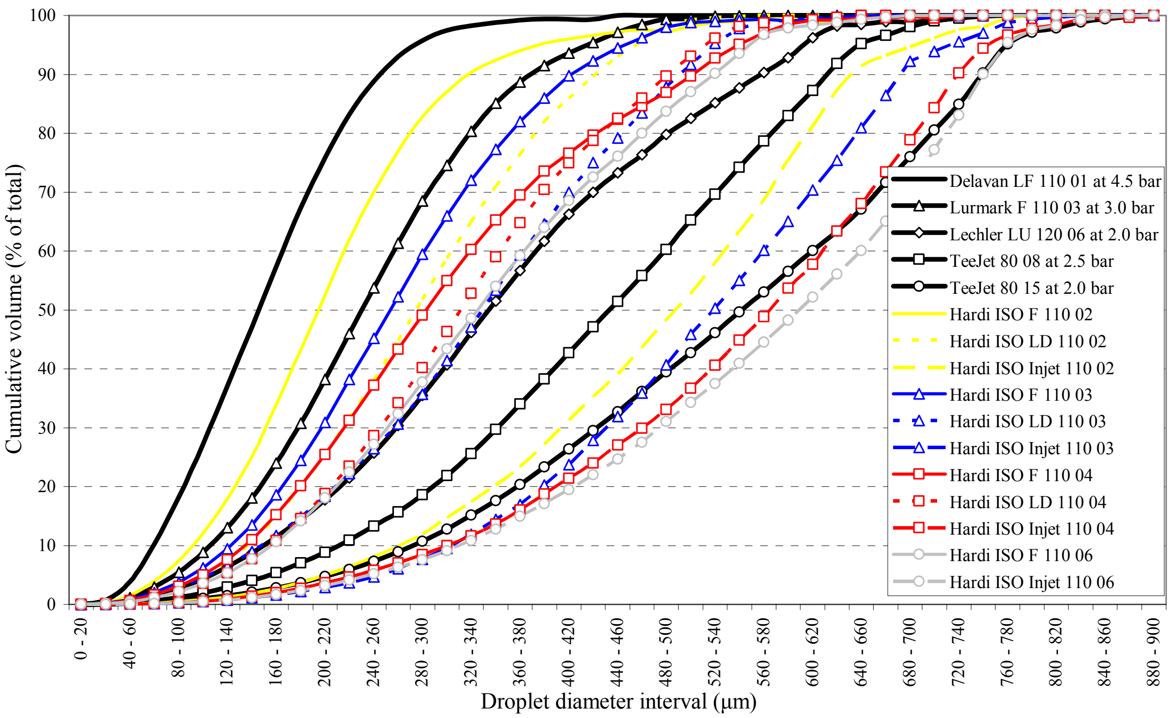

Figure 3.8: Cumulative volumetric droplet size distribution for different Hardi nozzles at a pressure of 3.0 bar and the five BCPC reference nozzle-pressure combinations

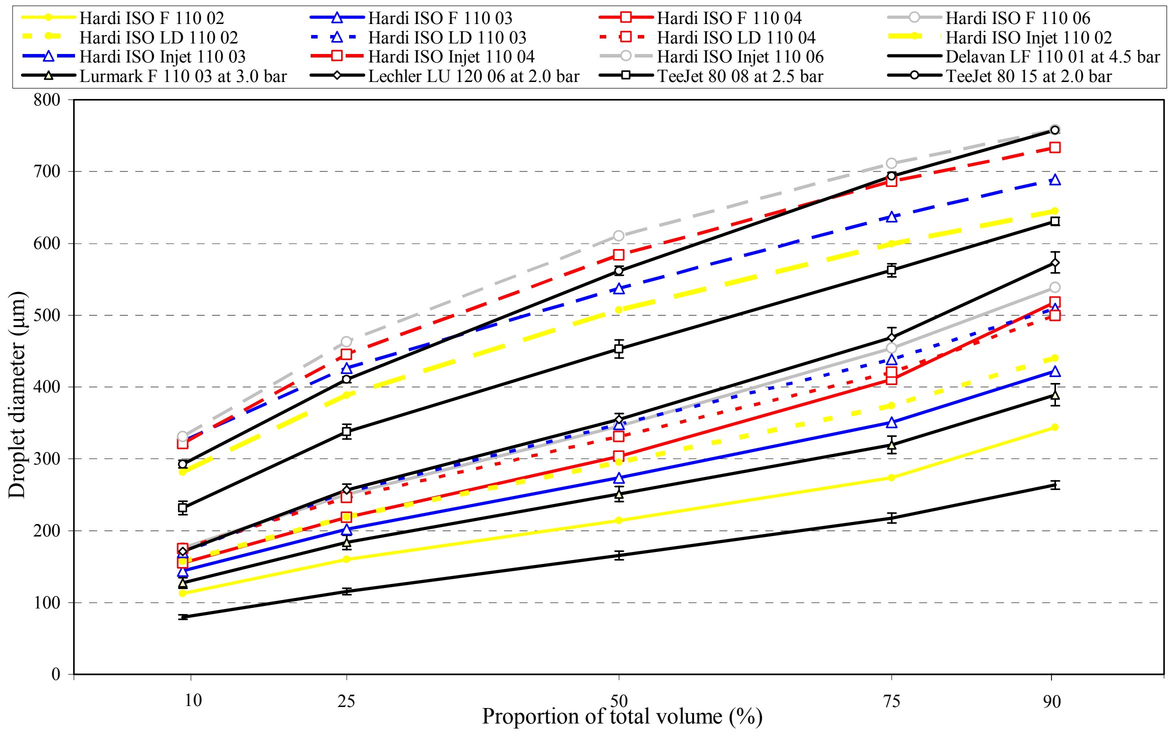

Figure 3.9: Droplet diameters below which smaller droplets constitute 10, 25, 50, 75 and 90% of the total volume ($D_{v0.1}$, $D_{v0.25}$, $D_{v0.5}$, $D_{v0.75}$ and $D_{v0.9}$) for the five BCPC reference nozzle-pressure combinations and for different Hardi nozzles at 3.0 bar

Table 3.3: Droplet size characteristics *BCPC*, $D_{v0.1}$, $D_{v0.25}$, $D_{v0.5}$, $D_{v0.75}$, $D_{v0.9}$, D_{10}, D_{20}, D_{30} and D_{32} (average ± standard deviation) of 18 nozzle-pressure combinations

Nozzle type	Pressure (bar)	*BCPC*	$D_{v0.1}$ (µm)	$D_{v0.25}$ (µm)	$D_{v0.5}$ (µm)	$D_{v0.75}$ (µm)	$D_{v0.9}$ (µm)	D_{10} (µm)	D_{20} (µm)	D_{30} (µm)	D_{32} (µm)
Delavan LF 110 01*	4.5	VF/F	79.7 ± 4.3	115.4 ± 6.2	165.4 ± 8.0	217.6 ± 9.1	263.5 ± 7.5	136.3 ± 5.2	99.6 ± 4.4	85.2 ± 4.3	71.3 ± 3.8
Lurmark F 110 03*	3.0	F/M	127.2 ± 10.2	183.8 ± 13.3	251.0 ± 14.0	319.4 ± 16.3	389.1 ± 20.3	206.7 ± 11.8	141.8 ± 8.3	117.5 ± 7.1	92.7 ± 5.7
Lechler LU 120 06*	2.0	M/C	170.8 ± 10.7	256.7 ± 10.7	355.0 ± 10.7	468.7 ± 18.8	573.5 ± 19.5	285.1 ± 10.4	180.7 ± 6.1	143.9 ± 4.8	108.6 ± 2.9
TeeJet 80 08*	2.5	C/VC	231.8 ± 12.5	337.7 ± 13.7	453.0 ± 17.2	562.5 ± 12.2	630.5 ± 7.3	365.4 ± 13.5	234.5 ± 9.7	187.8 ± 8.3	139.4 ± 5.9
TeeJet 80 15*	2.0	VC/EC	292.7 ± 7.1	410.3 ± 5.7	561.8 ± 8.3	693.6 ± 6.6	757.4 ± 4.7	452.7 ± 7.2	285.8 ± 8.4	227.1 ± 8.5	164.1 ± 7.5
Hardi ISO F 110 02	3.0	F	112.5 ± 10.7	159.8 ± 9.3	214.2 ± 7.9	273.7 ± 10.6	343.9 ± 29.9	181.1 ± 10.9	126.2 ± 9.1	105.4 ± 8.4	83.7 ± 6.9
Hardi ISO F 110 03	4.0	F	117.5 ± 5.5	174.0 ± 7.7	246.5 ± 6.7	325.5 ± 8.1	426.0 ± 28.0	201.2 ± 6.3	138.7 ± 4.5	115.2 ± 4.1	93.2 ± 3.2
Hardi ISO F 110 03$	3.0	M	144.1 ± 8.9	201.9 ± 9.1	273.6 ± 10.9	350.7 ± 14.0	421.9 ± 21.3	227.9 ± 8.2	152.9 ± 6.8	125.3 ± 6.8	96.0 ± 5.9
Hardi ISO F 110 03	2.0	M	131.2 ± 16.5	189.8 ± 25.1	265.4 ± 28.2	339.4 ± 21.7	399.3 ± 17.8	215.5 ± 21.2	148 ± 15.5	122.7 ± 13.4	97.1 ± 10.9
Hardi ISO F 110 04	3.0	M	154.9 ± 7.7	218.4 ± 7.2	303.4 ± 10.3	410.4 ± 21.8	518.3 ± 34.1	252.1 ± 9.9	163.1 ± 5.3	131.2 ± 4.0	98.7 ± 2.6
Hardi ISO F 110 06	3.0	M	176.1 ± 7.3	250.7 ± 7.0	345.1 ± 5.5	453.8 ± 6.1	538.7 ± 10.9	283.3 ± 6.9	181.2 ± 5.1	144.9 ± 4.5	107.1 ± 3.2
Hardi ISO LD 110 02	3.0	M	157.4 ± 7.6	218.9 ± 8.8	294.9 ± 9.7	374.2 ± 12.7	440.0 ± 16.2	245.8 ± 7.8	168.1 ± 6.0	139.0 ± 5.7	107.8 ± 4.6
Hardi ISO LD 110 03	3.0	M	169.8 ± 18.9	253.9 ± 18.9	348.2 ± 14.1	438.5 ± 9.0	509.3 ± 8.4	279.0 ± 17.4	185.1 ± 15.2	150.8 ± 13.9	116.7 ± 10.5
Hardi ISO LD 110 04	3.0	M	175.1 ± 3.7	246.0 ± 5.4	331.2 ± 6.4	420.3 ± 10.5	499.2 ± 11.9	275.9 ± 5.7	186.1 ± 4.1	152.9 ± 3.6	117.3 ± 3.0
Hardi ISO Injet 110 02	3.0	VC	281.6 ± 16	388.6 ± 19.5	506.8 ± 27	598.9 ± 31.0	644.7 ± 34.2	422.7 ± 20.4	290.0 ± 13.9	240.3 ± 13.8	181.1 ± 13.8
Hardi ISO Injet 110 03	3.0	VC	324.3 ± 11.2	426.5 ± 11.3	537.4 ± 16.9	637.2 ± 12.9	689.1 ± 8.2	464.8 ± 12.4	332.3 ± 19.6	281.2 ± 22.0	216.2 ± 23.2
Hardi ISO Injet 110 04	3.0	EC	321.3 ± 18.6	445.0 ± 23.5	584.0 ± 23.2	686.3 ± 20.4	733.5 ± 16.6	481.4 ± 19.7	325.0 ± 18.7	267.0 ± 17.8	198.4 ± 14.5
Hardi ISO Injet 110 06	3.0	EC	331.2 ± 12.6	463.1 ± 17.2	610.0 ± 21.2	711.0 ± 16.6	758.3 ± 15.7	499.5 ± 16.3	340.0 ± 15.5	280.5 ± 15.1	209.2 ± 13.3

* BCPC reference nozzle-pressure combinations; $ Reference nozzle pressure combination; *BCPC,* BCPC spray quality class; VF, very fine; F, fine; M, medium; C, coarse; VC, very coarse; EC, extremely coarse; $D_{v0.1}$, $D_{v0.25}$, $D_{v0.5}$, $D_{v0.75}$, $D_{v0.9}$, diameter below which smaller droplets constitute 10, 25, 50, 75 and 90 % of the total volume; D_{10}, D_{20}, D_{30}, D_{32}, arithmetic, surface, volume and sauter mean diameter

Table 3.4: Droplet size characteristics V_{50}, V_{75}, V_{100}, V_{150}, V_{200}, V_{250}, NMD, $\frac{D_{v0.5}}{NMD}$ and RSF (average ± standard deviation) of 18 nozzle-pressure combinations

Nozzle type	Pressure (bar)	V_{50} (%)	V_{75} (%)	V_{100} (%)	V_{150} (%)	V_{200} (%)	V_{250} (%)	NMD (µm)	$D_{v0.5}/NMD$	RSF
Delavan LF 110 01*	4.5	1.9 ± 0.3	8.5 ± 1.3	18.3 ± 2.4	42.0 ± 3.6	67.4 ± 3.9	86.2 ± 2.5	59.6 ± 3.3	2.8 ± 0.2	1.1 ± 0.1
Lurmark F 110 03*	3.0	0.6 ± 0.1	2.4 ± 0.5	5.5 ± 1.2	15.4 ± 3.0	30.8 ± 4.6	50.0 ± 5.7	68.6 ± 3.5	3.7 ± 0.2	1.0 ± 0.1
Lechler LU 120 06*	2.0	0.2 ± 0.0	1.2 ± 0.1	2.7 ± 0.3	7.5 ± 1.1	14.4 ± 1.9	23.5 ± 2.4	74.7 ± 1.6	4.8 ± 0.2	1.1 ± 0.1
TeeJet 80 08*	2.5	0.1 ± 0.0	0.5 ± 0.1	1.2 ± 0.2	3.5 ± 0.6	7.0 ± 1.0	12.1 ± 1.5	89.8 ± 2.8	5.0 ± 0.2	0.9 ± 0.1
TeeJet 80 15*	2.0	0.0 ± 0.0	0.3 ± 0.0	0.6 ± 0.1	1.7 ± 0.2	3.7 ± 0.4	6.6 ± 0.5	99.3 ± 5.9	5.7 ± 0.4	0.8 ± 0.0
Hardi ISO F 110 02	3.0	0.8 ± 0.2	3.2 ± 0.8	7.4 ± 1.8	21.6 ± 3.6	43.2 ± 4.0	66.0 ± 3.8	64.1 ± 5.6	3.4 ± 0.3	1.1 ± 0.1
Hardi ISO F 110 03	4.0	0.6 ± 0.1	2.8 ± 0.4	6.6 ± 0.9	18.1 ± 2.2	33.5 ± 2.6	51.1 ± 2.4	71.8 ± 2.6	3.4 ± 0.2	1.3 ± 0.1
Hardi ISO F 110 03$	3.0	0.4 ± 0.1	1.6 ± 0.3	3.7 ± 0.7	11.4 ± 1.8	24.5 ± 2.9	41.6 ± 3.5	67.9 ± 5.1	4.1 ± 0.4	1.0 ± 0.1
Hardi ISO F 110 03	2.0	0.5 ± 0.2	2.1 ± 0.7	5.3 ± 2.1	15.2 ± 6.0	28.7 ± 8.5	44.5 ± 9.3	72.8 ± 5.7	3.6 ± 0.3	1.0 ± 0.1
Hardi ISO F 110 04	3.0	0.4 ± 0.0	1.3 ± 0.2	3.0 ± 0.4	9.2 ± 1.3	20.1 ± 1.8	34.2 ± 2.5	67.7 ± 2.1	4.5 ± 0.2	1.2 ± 0.1
Hardi ISO F 110 06	3.0	0.3 ± 0.0	1.0 ± 0.1	2.2 ± 0.3	6.5 ± 0.8	14.2 ± 1.4	24.8 ± 1.6	70.8 ± 2.6	4.9 ± 0.2	1.1 ± 0.0
Hardi ISO LD 110 02	3.0	0.3 ± 0.0	1.3 ± 0.2	2.9 ± 0.4	8.8 ± 1.3	19.9 ± 2.3	34.8 ± 3.2	76.2 ± 3.0	3.9 ± 0.2	1.0 ± 0.0
Hardi ISO LD 110 03	3.0	0.2 ± 0.1	1.1 ± 0.3	2.7 ± 0.8	7.7 ± 2.1	14.8 ± 3.2	24.2 ± 4.0	82.5 ± 5.4	4.2 ± 0.2	1.0 ± 0.1
Hardi ISO LD 110 04	3.0	0.2 ± 0.0	0.9 ± 0.1	2.1 ± 0.2	6.4 ± 0.5	14.5 ± 0.9	26.0 ± 1.3	81.7 ± 3.3	4.1 ± 0.1	1.0 ± 0.0
Hardi ISO Injet 110 02	3.0	0.0 ± 0.0	0.2 ± 0.0	0.5 ± 0.1	1.5 ± 0.2	3.7 ± 0.5	7.2 ± 1.3	122.1 ± 17.9	4.2 ± 0.7	0.7 ± 0.0
Hardi ISO Injet 110 03	3.0	0.0 ± 0.0	0.1 ± 0.0	0.3 ± 0.1	0.9 ± 0.3	2.2 ± 0.5	4.2 ± 0.8	152.6 ± 35.4	3.7 ± 0.8	0.7 ± 0.0
Hardi ISO Injet 110 04	3.0	0.0 ± 0.0	0.1 ± 0.0	0.3 ± 0.1	1.1 ± 0.3	2.8 ± 0.6	5.2 ± 0.9	134.4 ± 13.8	4.4 ± 0.4	0.7 ± 0.0
Hardi ISO Injet 110 06	3.0	0.0 ± 0.0	0.1 ± 0.0	0.3 ± 0.1	0.9 ± 0.2	2.3 ± 0.4	4.7 ± 0.6	146.0 ± 17.0	4.2 ± 0.4	0.7 ± 0.0

* BCPC reference nozzle-pressure combinations; $ Reference nozzle pressure combination; V_{50}, V_{75}, V_{100}, V_{150}, V_{200}, V_{250}, proportion of total volume of droplets smaller than 50, 75, 100, 150, 200 and 250 µm in diameter; NMD, number median diameter; $D_{v0.5}$, volume mean diameter; RSF, relative span factor

3.3.2.1. Effect of nozzle type

Often in the analysis of droplet distributions, interactions among formulation (Miller & Butler Ellis, 1997; Butler Ellis *et al*., 2001), nozzle types (Barnett & Matthews, 1992; Miller, 1999) and operating pressures (Ozkan, 1998; Etheridge *et al*., 1999) are observed. That is why measurements to investigate the effect of nozzle type are carried out at a constant pressure of 3.0 bar with water at a constant temperature of 20°C. For the same nozzle size and pressure, standard flat fan nozzles produce the finest droplet size spectrum and thus the highest proportion of droplets prone to drift, followed by low-drift flat fan nozzles and air injection nozzles. This can be concluded from the different droplet size characteristics for the different nozzle-pressure combinations in Table 3.3 and Table 3.4.

In Figure 3.10, V_{100} values are presented for the different Hardi nozzle-pressure combinations together with the 95% confidence intervals and in Annex 3 for the V_{50}, V_{75}, V_{150}, V_{200} and V_{250} characteristics. A significant difference in the proportion of small droplets between the different nozzle types is found using the t-test (α = 0.05). For example, at a pressure of 3.0 bar and for ISO 02 nozzle sizes, values for V_{100} and V_{200} vary from 0.5 and 3.7% for the air inclusion nozzles up to 2.9 and 19.9% for the low-drift nozzles and 7.4 and 43.2% for the standard flat fan nozzles which is important with regard to driftability. The same can be concluded for the characteristics V_{50}, V_{75}, V_{150} and V_{250}, and for the other nozzle sizes (ISO 03, 04 and 06) (Table 3.4) but it is noticeable that the effect of nozzle type is more important for smaller nozzle sizes. Especially for the air inclusion nozzles, the amount of droplets smaller than 100 μm is very low and less than 0.5% of the total spray volume. Similar results were found by other researchers like Barnett and Matthews (1992) and Combellack *et al*. (1996).

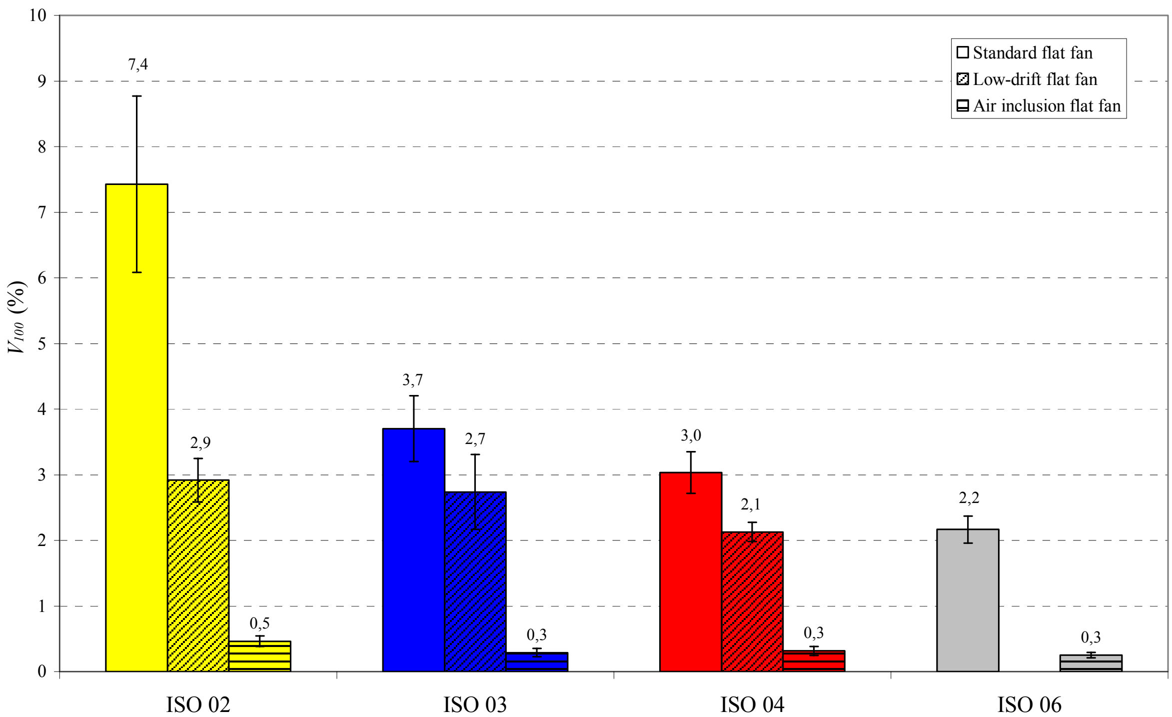

Figure 3.10: Proportion of total volume in % of droplets smaller than 100 μm in diameter for the different Hardi nozzle types at a pressure of 3.0 bar together with the 95% confidence intervals

Although there is no specific droplet size range that is liable to drift under all conditions, many researchers have considered droplets smaller than 75 μm (Miller & Hadfield, 1989;

Hobson *et al*., 1990), 100 µm (Grover *et al*., 1978; Byass & Lake, 1977), 150 µm (Yates *et al*., 1985; Combellack *et al*., 1996) or 200 µm (Bouse *et al*., 1990) to be the most drift-prone. It is important to note that for air injection nozzles in general, and for ISO 02 and 03 Injet nozzles in particular, V_{100} values (0.5 and 0.3%) are smaller than one would expect regarding the V_{100} values of the reference nozzles of the BCPC nozzle class they belong to, namely, very coarse. The corresponding reference nozzles TeeJet 80 08 at 2.5 bar (C/VC) and TeeJet 80 15 at 2.0 bar (VC/EV) have V_{100} values of 1.2 and 0.6%. This is important with regard to the classification of nozzles based on their driftability and it can also be deduced from the low *RSF* values for the air inclusion nozzles. Although it is possible to reduce the proportion of drift-prone droplets using low-drift or air inclusion nozzles, there is a concern that because of the larger droplets an increased run-off and a reduction in efficacy of foliar-acting pesticides may occur (Jensen, 1999; Wolf, 2002). Heinkel *et al*. (2000), Shaw *et al*. (2000) and Frieβleben (2004) found that low-drift and air injection nozzles can provide similar performance to conventional sprays provided the operator is given information on how to make initial nozzle selections and optimize their performance.

The relative span factor (*RSF*) indicates the range or spread of droplet sizes in a spray by calculating the spectrum width ($D_{v0.9}$ - $D_{v0.1}$) relative to the $D_{v0.5}$ value. *RSF* values are highest for the standard flat fan nozzles (varying from 1.015 up to 1.197) followed by the low-drift flat fan nozzles (varying from 0.958 up to 0.978), but differences are rather small. For the ISO 03 nozzle size, no significant difference between the low-drift and the standard flat fan nozzles was found (significance level $\alpha = 0.05$, t-test). On the other hand, *RSF* values for the different air inclusion nozzles are clearly lower compared with the other types, varying from 0.680 (ISO 03) up to 0.716 (ISO 02). This is mainly due to the high $D_{v0.5}$ values. The relative span factor is a dimensionless parameter indicative of the uniformity of the drop size distribution. An overview of the *RSF* values together with their 95% confidence intervals can be found in Figure 3.11.

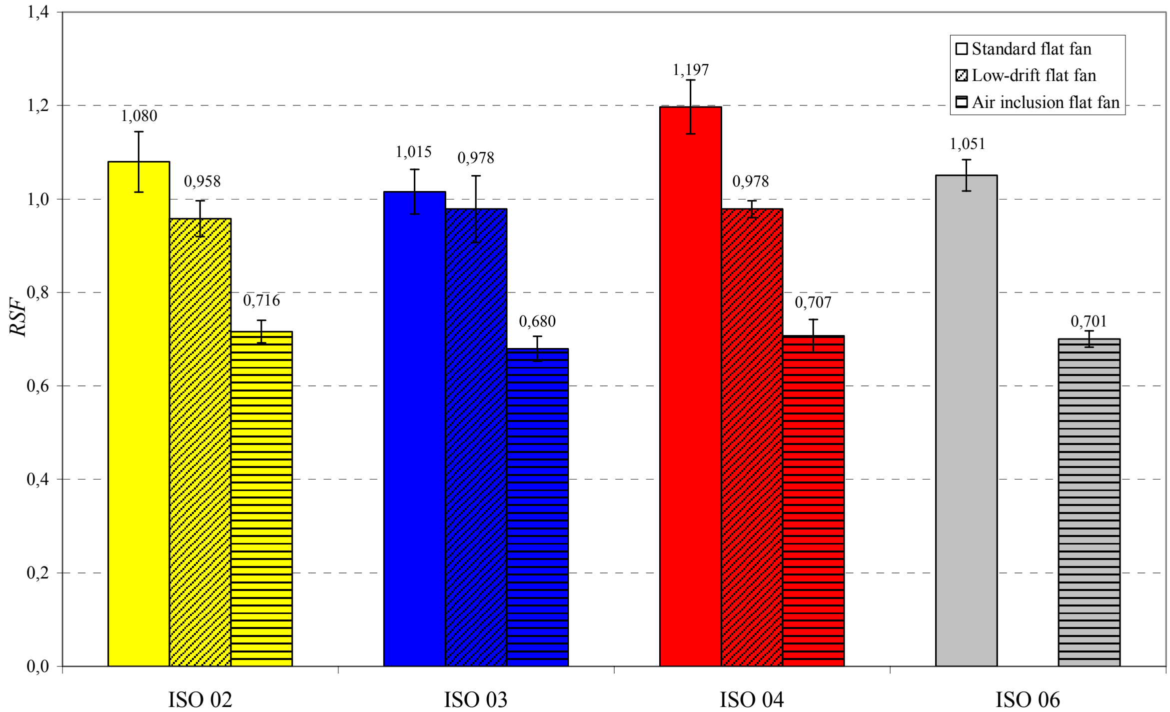

Figure 3.11: Relative span factors ($RSF = \frac{D_{v0.9} - D_{v0.1}}{D_{v0.5}}$) for the different Hardi nozzle types at a pressure of 3.0 bar together with the 95% confidence intervals

The volume median diameter ($D_{v0.5}$) is the most commonly used descriptor of droplet size and $D_{v0.5}$ values of the different nozzle-pressure combinations also reflect the effect of nozzle type on droplet size characteristics as presented in Table 3.3. For example $D_{v0.5}$ values were significantly different ($\alpha = 0.05$) and, respectively, 273.6, 348.2 and 537.4 µm for standard, low-drift and air-inclusion ISO 03 nozzles at a pressure of 3.0 bar. Similar results are found for values of $D_{v0.25}$, $D_{v0.75}$, $D_{v0.9}$, D_{10}, D_{20}, D_{30} and D_{32} and for other nozzle sizes. At a pressure of 3.0 bar, all of the standard and the low-drift flat fan nozzles are BCPC classified as 'medium', except the ISO 02 standard flat fan nozzle which is classified as 'fine'. The air inclusion nozzles are classified as 'very coarse' for the 02 and 03 ISO nozzle sizes and 'extremely coarse' for the bigger 04 and 06 ISO nozzles sizes. Remarkably, none of the tested nozzles is classified as 'coarse'.

3.3.2.2. Effect of nozzle size

In general, the larger the ISO (International Organisation for Standardization) nozzle size, the coarser is the droplet size spectrum at the same pressure (Figure 3.8, Figure 3.9, Table 3.3 and Table 3.4). For example $D_{v0.5}$ values were, respectively, 214.2, 273.6, 303.4 and 345.4 µm for ISO 02, 03, 04 and 06 Hardi standard flat fan nozzles at a pressure of 3.0 bar. This emphasizes the need for effective drift control practices in systems with low application volumes. Droplet size characteristics of the Hardi ISO F 110 06 nozzle are nearly equal to the droplet size characteristics of the Hardi ISO LD 110 03 nozzle both operating at a pressure of 3.0 bar and delivering a totally different output, respectively, 1.2 $L.min^{-1}$ and 2.4 $L.min^{-1}$. In Figure 3.12, $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ values are presented for the different Hardi nozzles at a spray pressure of 3.0 bar together with the 95% confidence intervals using the t-distribution ($\alpha = 0.05$; df = 8).

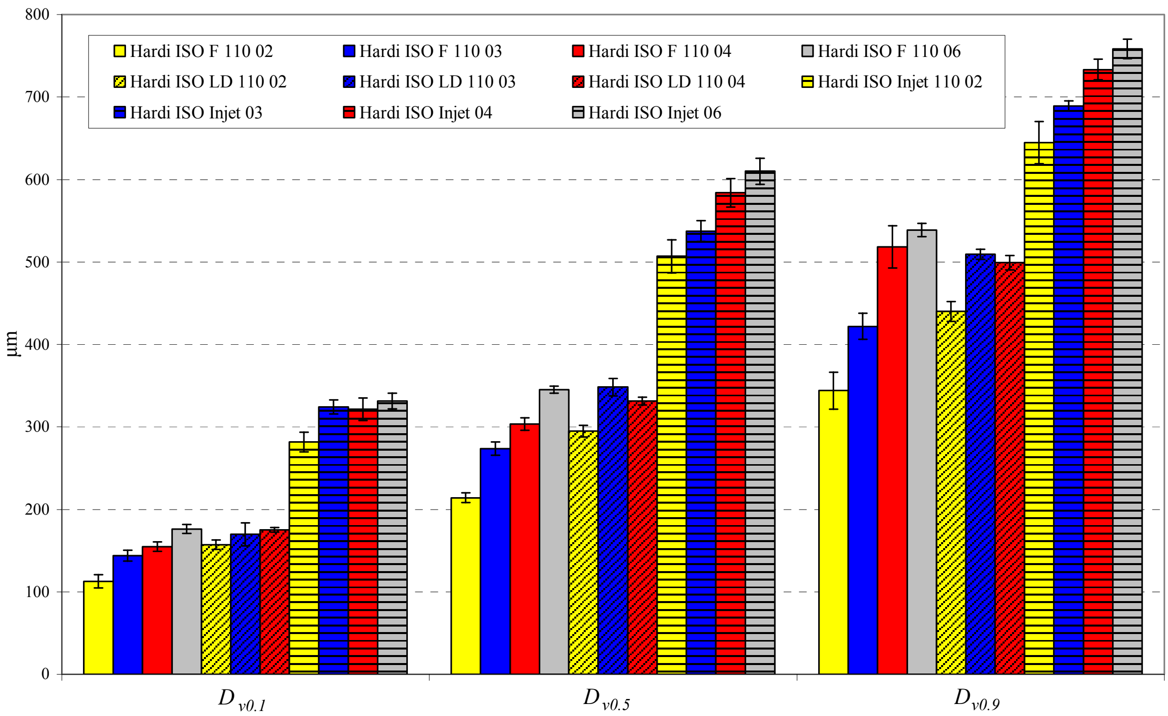

Figure 3.12: Volume diameters below which smaller droplets constitute 10, 50 and 90 % of the total spray volume ($D_{v0.1}$, $D_{v0.25}$, $D_{v0.75}$, $D_{v0.9}$) and the 95% confidence intervals for different Hardi nozzles at a pressure of 3.0 bar

Consequently, the proportion of small droplets (e.g. V_{100}) also increases with smaller nozzle sizes and this effect is more important for the standard flat fan nozzles than for the low-drift flat fan nozzles. This is confirmed by previous studies carried out by Barnett and Matthews (1992) and Etheridge *et al.* (1999) and it is illustrated in Figure 3.10 for V_{100} and in Annex 3 for V_{50}, V_{75}, V_{150}, V_{200} and V_{250}. For example, at a pressure of 3.0 bar and for standard flat fan nozzles, V_{100} values were, respectively, 2.2, 3.0, 3.7 and 7.4% for ISO 06, 04, 03 and 02 nozzle sizes. For the low-drift flat fan nozzles, V_{100} values were 2.1, 2.7 and 2.9% for the ISO 04, 03 and 02 nozzle sizes.

For the air inclusion nozzles, the effect of nozzle size on the proportion of small droplets is less important and the proportion of small droplets is low in all cases. This is presented in Figure 3.10 for V_{100}. On the other hand, at the higher end of the droplet size spectrum ($D_{v0.5}$ and $D_{v0.9}$), nozzle size does have an effect on droplet characteristics for air inclusion nozzles with $D_{v0.5}$ values of 506.8, 537.4, 584.0 and 610.0 μm and $D_{v0.9}$ values of 644.7, 689.1, 733.5 and 758.3 μm for the Injet ISO 02, 03, 04 and 06 nozzles sizes at 3.0 bar. Butler Ellis *et al.* (2002) also found that the relationship between nozzle size and droplet size that holds for conventional nozzles does not necessarily apply to air inclusion nozzles, so that droplet size is independent of nozzle size.

The only exception was found for the Hardi ISO LD 110 03 and 110 04 where the total droplet size spectrum of the LD 110 03 is slightly coarser than the LD 110 04 at a pressure of 3.0 bar. This is confirmed statistically for the $D_{v0.5}$ values which are significantly different (t-test, $\alpha = 0.05$). Despite this difference, both nozzle-pressure combinations are BCPC classified as ‘medium’ which illustrates that the difference between both is rather small.

3.3.2.3. Effect of spray pressure

A rather limited series of measurements was carried out to investigate the effect of operating pressure on droplet size characteristics. Measurements were done with the Hardi ISO F 110 03 standard flat fan nozzles at pressures of 2.0, 3.0 and 4.0 bar. In Figure 3.13, droplet size characteristics $D_{v0.1}$, $D_{v0.25}$, $D_{v0.5}$, $D_{v0.75}$, $D_{v0.9}$ are presented together with their 95% confidence intervals. From these results, it can be concluded that increasing the spray pressure from 3.0 to 4.0 bar significantly decreases the droplet size (t-test, $\alpha = 0.05$) but the effect is very limited compared to the effect of nozzle size and type. Remarkably, when the pressure was decreased from 3.0 to 2.0 bar, there was no significant effect ($\alpha = 0.05$) on the droplet size characteristics $D_{v0.1}$, $D_{v0.25}$, $D_{v0.75}$, $D_{v0.9}$ and droplet sizes even tended to decrease.

Operating pressure also seems to influence the repeatability of the measurements. Standard deviations between measurements were highest for the low operating pressure of 2.0 bar and lowest for the high operating pressure of 4.0 bar (Table 3.3 and Table 3.4). This can also be concluded from the width of the 95% confidence intervals of the characteristics $D_{v0.1}$, $D_{v0.25}$, $D_{v0.75}$, $D_{v0.9}$ in Figure 3.13. This was already concluded before by Derksen *et al.* (1999).

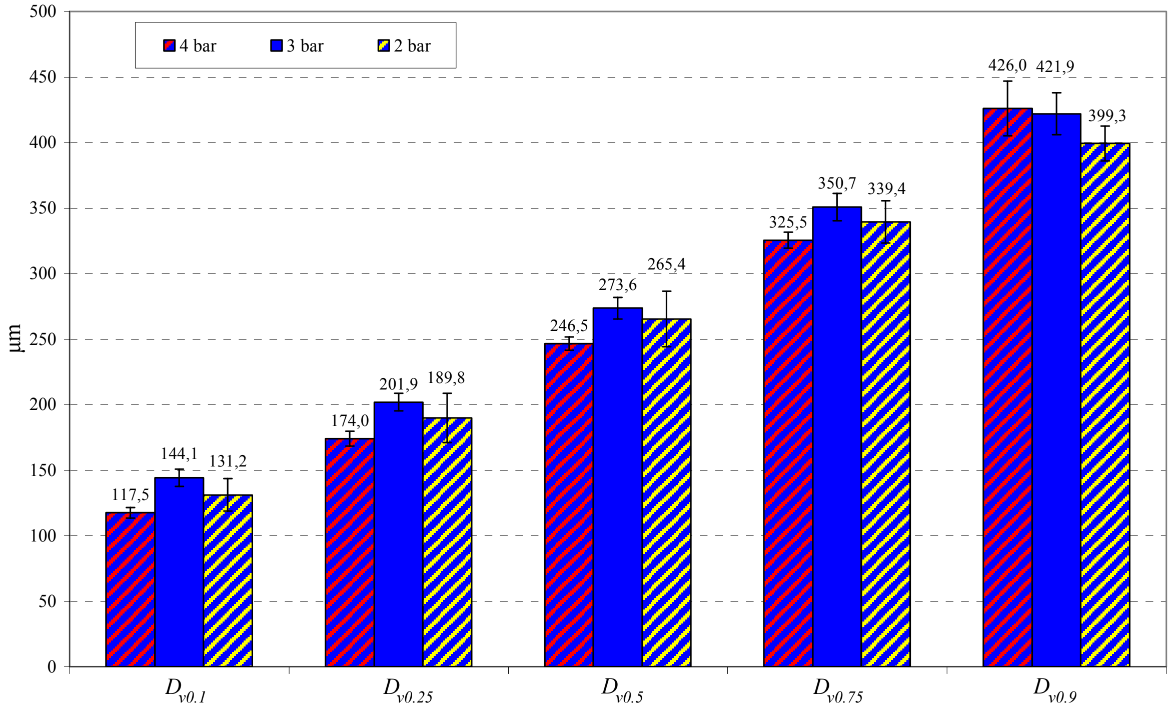

Figure 3.13: Volume diameters below which smaller droplets constitute 10, 25, 50, 75 and 90% of the total spray volume ($D_{v0.1}$, $D_{v0.25}$, $D_{v0.5}$, $D_{v0.75}$, $D_{v0.9}$) and the 95% confidence intervals (t-distribution, α = 0.05, df = 8) for the Hardi ISO F 110 03 nozzle at pressures of 2.0, 3.0 and 4.0 bar

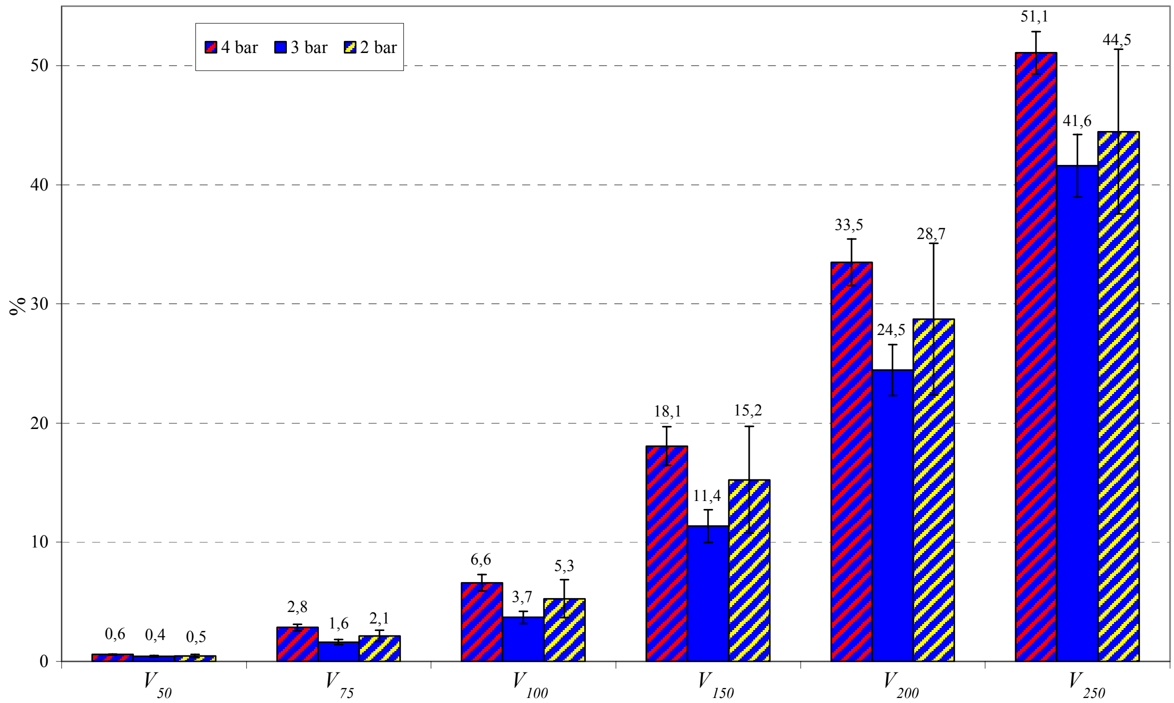

Figure 3.14: Proportion of total volume in % of droplets smaller than 50, 75, 100, 150, 200 and 250 µm in diameter (V_{50}, V_{75}, V_{100}, V_{150}, V_{200}, V_{250}) for the Hardi ISO F 110 03 nozzle at spray pressures of 2.0, 3.0 and 4.0 bar together with the 95% confidence intervals (t-distribution, α = 0.05, df = 8)

Logically, similar conclusions can be taken for the effect of spray pressure on the proportion of small droplets expressed by V_{50}, V_{75}, V_{100}, V_{150}, V_{200}, V_{250} which are presented in Figure 3.14. Increasing the spray pressure from 3.0 to 4.0 bar increases the proportion of small droplets significantly ($\alpha = 0.05$). For example, values for V_{100} and V_{200} raise from 3.7 and 24.5%, at a pressure of 3.0 bar, up to 6.6 and 33.5% at a pressure of 4.0 bar. Again, there was no significant effect ($\alpha = 0.05$) of lowering the operating pressure from 3.0 to 2.0 bar on the amount of small droplets although there is a tendency that the amount of small droplets increases which is in contrast with previous studies (Barnett & Matthews, 1992; Etheridge *et al*., 1999). This rather unexpected response on droplet size characteristics when lowering spray pressure is likely due to flow turbulence within the nozzle (Etheridge *et al*., 1999).

In general, it is clear that for the Hardi ISO 110 03 standard flat fan nozzle, the effect of spray pressure is rather limited within a pressure range from 2.0 to 4.0 bar compared to the effect of nozzle size and type. This type of nozzle is BCPC classified as 'fine' at a pressure of 4.0 bar and as 'medium' at pressures of 2.0 and 3.0 bar.

3.3.3. Droplet velocity characteristics

Droplet velocities were measured in one dimension (i.e. the vertical dimension) at a distance of 0.50 m from the spray nozzle. Besides the droplets velocity spectra, different droplet velocity characteristics are calculated:

- v_{vol10}, v_{vol25}, v_{vol50}, v_{vol75}, v_{vol90} – droplet velocity in m.s^{-1} below which slower droplets constitute 10, 25, 50, 75, 90% of the total spray volume,
- v_{avg} – arithmetic average droplet velocity in m.s^{-1},
- *VSF* – velocity span factor, a dimensionless parameter indicative of the uniformity of the drop size velocity distribution, defined as:

$$VSF = \frac{v_{vol0.9} - v_{vol0.1}}{v_{vol0.5}} \qquad (3.8)$$

Similar to droplet size spectrum, each nozzle-pressure combination produces a droplet velocity spectrum with velocities varying from about 0 m.s^{-1} up to 16 m.s^{-1}. This is illustrated in Figure 3.15 which presents the cumulative volumetric droplet velocity distribution for different Hardi nozzle-pressure combinations and the reference nozzles, and in Figure 3.16 presenting droplet velocity characteristics v_{vol10}, v_{vol25}, v_{vol50}, v_{vol75}, v_{vol90} for the same nozzle-pressure combinations.

Again, variations in droplet velocities are important with regard to aspects of driftability, crop penetration and retention by the plant surfaces. A complete overview of the different droplet velocity characteristics is given in Table 3.5. Average values and standard deviations based on nine repetitions are presented. Standard deviations are small, indicating a good repeatability of the measurements. Remark that in some cases, for a very small proportion of the total volume of spray droplets a negative one-dimensional droplet speed was measured. This is caused by small droplets rebounding from the floor and small floating droplets crossing the measuring volume. That is why the proportion of the total volume of droplets with a negative speed is highest for nozzle-pressure combinations creating a very fine spray (e.g. Delavan LF 110 01 at 4.5 bar and Hardi ISO F 110 02 at 3.0 bar).

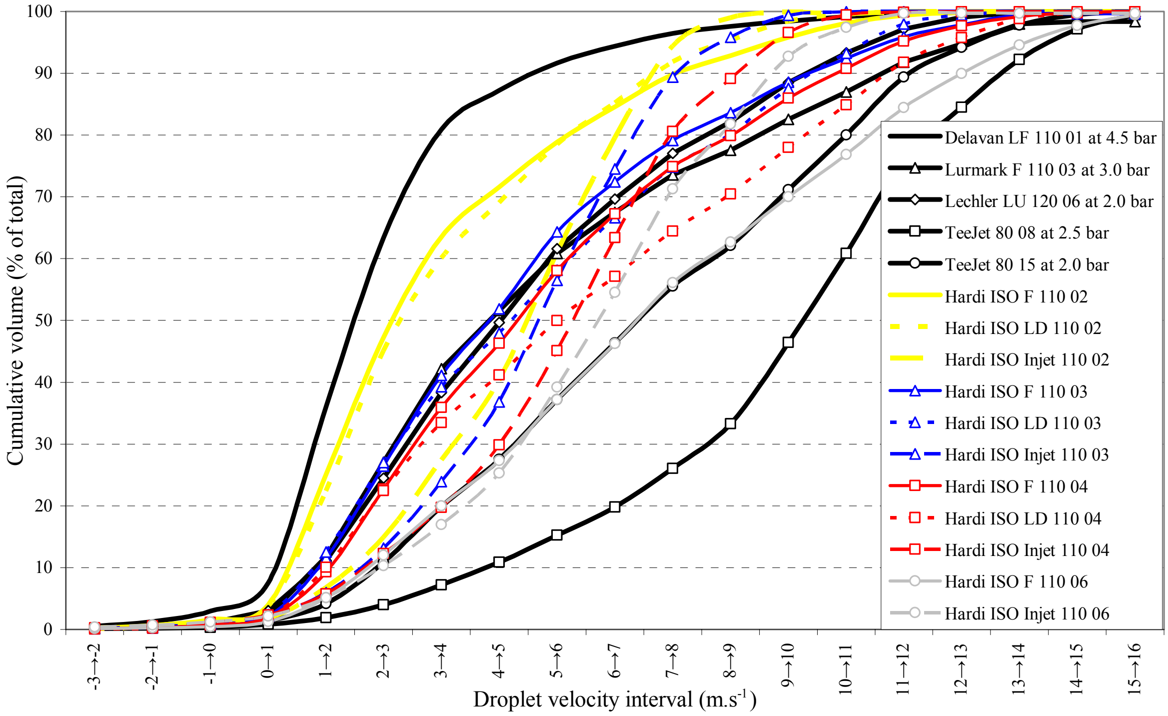

Figure 3.15: Cumulative volumetric droplet velocity distribution for different Hardi nozzles at 3.0 bar and the five BCPC reference nozzle-pressure combinations

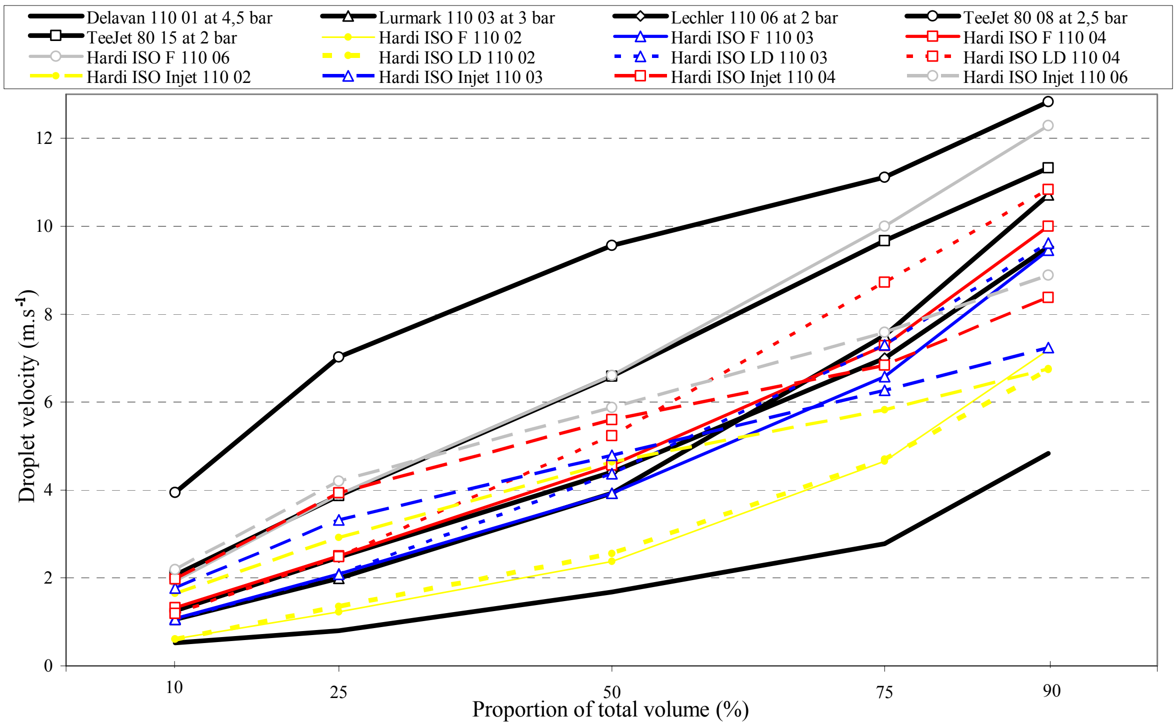

Figure 3.16: Droplet velocities below which slower droplets constitute 10, 25, 50, 75 and 90% of the total volume *(v_{vol10}, v_{vol25}, v_{vol50}, v_{vol75}, v_{vol90})* for the five BCPC reference nozzle-pressure combinations and for different Hardi nozzles at 3.0 bar

Table 3.5: Droplet velocity characteristics v_{vol10}, v_{vol25}, v_{vol50}, v_{vol75}, v_{vol90}, v_{avg} and *VSF* (average ± standard deviation) of 18 nozzle-pressure combinations

Nozzle type	Pressure (bar)	v_{vol10} (m.s^{-1})	v_{vol25} (m.s^{-1})	v_{vol50} (m.s^{-1})	v_{vol75} (m.s^{-1})	v_{vol90} (m.s^{-1})	v_{avg} (m.s^{-1})	*VSF*
Delavan LF 110 01*	4.5	0.5 ± 0.1	0.8 ± 0.2	1.7 ± 0.2	2.8 ± 0.3	4.8 ± 0.6	1.2 ± 0.1	2.6 ± 0.2
Lurmark F 110 03*	3.0	1.1 ± 0.2	2.0 ± 0.2	3.9 ± 0.5	7.5 ± 1.1	10.7 ± 0.8	2.0 ± 0.2	2.5 ± 0.3
Lechler LU 120 06*	2.0	1.3 ± 0.2	2.5 ± 0.2	4.4 ± 0.3	7.0 ± 0.4	9.5 ± 0.3	1.9 ± 0.1	1.9 ± 0.2
TeeJet 80 08*	2.5	3.9 ± 0.3	7.0 ± 0.4	9.6 ± 0.2	11.1 ± 0.3	12.8 ± 0.3	3.5 ± 0.1	0.9 ± 0.2
TeeJet 80 15*	2.0	2.1 ± 0.2	3.9 ± 0.3	6.6 ± 0.3	9.7 ± 0.2	11.3 ± 0.3	2.8 ± 0.1	1.4 ± 0.1
Hardi ISO F 110 02	3.0	0.6 ± 0.0	1.2 ± 0.3	2.4 ± 0.3	4.7 ± 0.3	7.2 ± 0.6	1.3 ± 0.2	2.8 ± 0.2
Hardi ISO F 110 03	4.0	0.9 ± 0.2	1.8 ± 0.4	3.8 ± 0.8	7.7 ± 1.4	11.3 ± 1.5	2.0 ± 0.3	2.7 ± 0.3
Hardi ISO F 110 03$	3.0	1.1 ± 0.2	2.1 ± 0.3	3.9 ± 0.4	6.6 ± 0.4	9.5 ± 0.6	1.5 ± 0.2	2.1 ± 0.3
Hardi ISO F 110 03	2.0	0.9 ± 0.2	1.8 ± 0.3	3.3 ± 0.5	5.4 ± 0.5	8.2 ± 0.5	1.6 ± 0.2	2.2 ± 0.3
Hardi ISO F 110 04	3.0	1.3 ± 0.1	2.5 ± 0.1	4.6 ± 0.2	7.3 ± 0.4	10.0 ± 0.4	1.8 ± 0.1	1.9 ± 0.1
Hardi ISO F 110 06	3.0	1.9 ± 0.2	3.9 ± 0.4	6.6 ± 0.2	10.0 ± 0.4	12.3 ± 0.4	2.4 ± 0.1	1.6 ± 0.2
Hardi ISO LD 110 02	3.0	0.6 ± 0.0	1.4 ± 0.2	2.6 ± 0.1	4.7 ± 0.2	6.7 ± 0.2	0.9 ± 0.1	2.4 ± 0.1
Hardi ISO LD 110 03	3.0	1.1 ± 0.2	2.1 ± 0.4	4.4 ± 0.4	7.3 ± 0.4	9.6 ± 0.3	1.6 ± 0.1	2.0 ± 0.2
Hardi ISO LD 110 04	3.0	1.2 ± 0.2	2.5 ± 0.2	5.2 ± 0.4	8.7 ± 0.2	10.8 ± 0.2	1.8 ± 0.1	1.8 ± 0.1
Hardi ISO Injet 110 02	3.0	1.6 ± 0.1	2.9 ± 0.3	4.6 ± 0.0	5.8 ± 0.2	6.8 ± 0.2	1.3 ± 0.1	1.1 ± 0.1
Hardi ISO Injet 110 03	3.0	1.8 ± 0.3	3.3 ± 0.2	4.8 ± 0.1	6.3 ± 0.2	7.2 ± 0.3	1.9 ± 0.2	1.1 ± 0.1
Hardi ISO Injet 110 04	3.0	2.0 ± 0.2	3.9 ± 0.3	5.6 ± 0.1	6.8 ± 0.2	8.4 ± 0.4	2.0 ± 0.2	1.1 ± 0.1
Hardi ISO Injet 110 06	3.0	2.2 ± 0.3	4.2 ± 0.2	5.9 ± 0.3	7.6 ± 0.5	8.9 ± 0.4	2.3 ± 0.2	1.1 ± 0.1

* BCPC reference nozzle-pressure combinations; $ Reference nozzle pressure combination; v_{vol10}, v_{vol25}, v_{vol50}, v_{vol75}, v_{vol90}, droplet velocity below which slower droplets constitute 10, 25, 50, 75 and 90% of the total spray volume; v_{avg}, arithmetic average droplet velocity; *VSF*, velocity span factor

3.3.3.1. Relation between droplet size and droplet velocity

Before looking at the effect of nozzle type, size and spray pressure, a possible relation between droplet sizes and droplet velocities from the spray nozzle is investigated. Sidahmed *et al.* (1999) already investigated the correlations between droplet sizes and velocities at the formation of sprays from flat fan nozzles by measuring at a distance of 0.04 m below the nozzle. They concluded that droplet velocities are fairly constant for the different droplet sizes down to a droplet size of about 70 µm. For these droplets, velocities of about 16 to 18 $m.s^{-1}$ were measured depending on the nozzle type. Below 70 µm, droplet velocities consistently decreased with the decrease of droplet size down to velocities of 10 to 12 $m.s^{-1}$ for the smallest droplets. According to Dombrowski and Johns (1963), sprays leave the nozzle at velocities in the range of 15 to 25 $m.s^{-1}$.

In this study, droplet characteristics were measured at a distance of 0.50 m below the nozzle for different nozzle types and spray pressures. In Figure 3.17, the average droplet velocities for the different droplet size classes are shown for different Hardi nozzles at a pressure of 3.0 bar. From this graph, it is clear that there is a strong correlation between droplet sizes and velocities at a distance of 0.50 m below the nozzle. In general, bigger droplet sizes correspond with higher droplet velocities, small droplets with lower droplet velocities. For the bigger droplet sizes (> 400 µm) droplet velocities are relatively constant and vary from about 4.5 up to 8.5 $m.s^{-1}$ depending on the nozzle type and size. Below 400 µm, droplet velocities consistently decrease with the decrease of drop size. Also for the smallest droplets, droplet velocities are different for one and the same droplet size interval and vary from 0.5 to 2 $m.s^{-1}$ depending on nozzle size and type. The effect of nozzle type, size and pressure on droplet velocities is discussed in more detail in sections 3.3.3.2 up to 3.3.3.4.

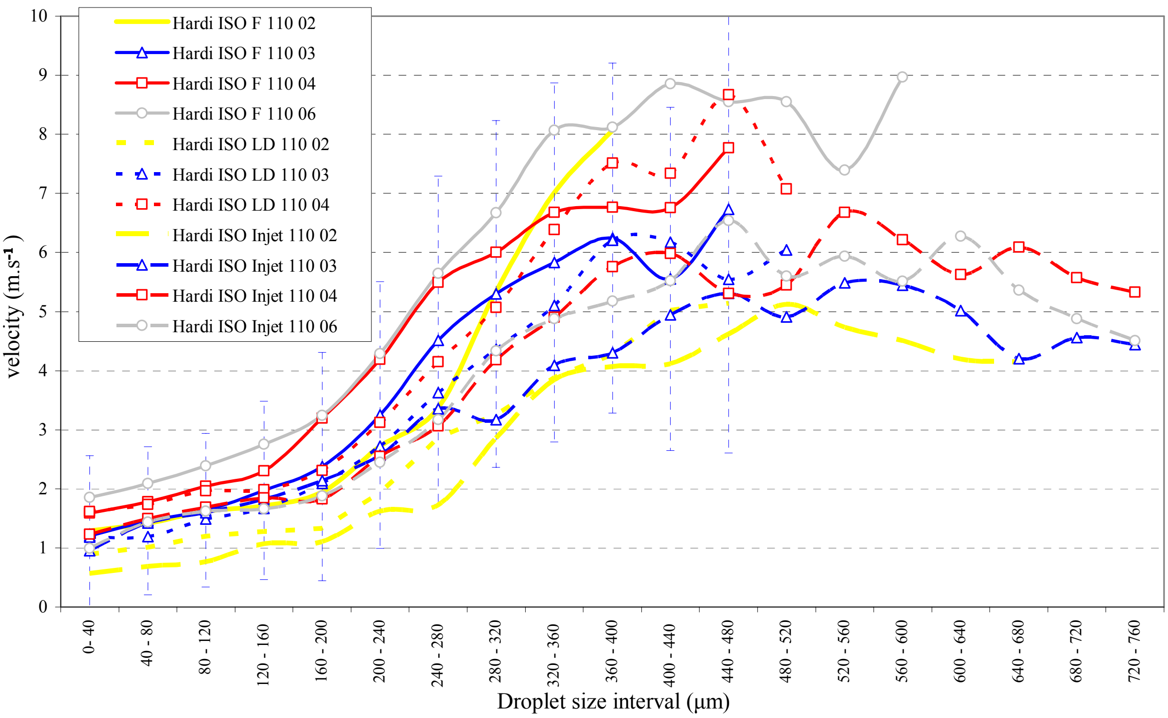

Figure 3.17: Average droplet velocities for the different droplet size classes of different Hardi nozzles at a pressure of 3.0 bar

Based on previous investigations measuring droplet velocities near the exit of the nozzle (Dombrowski & Johns, 1963; Sidahmed *et al*., 1999) and the presented measurements at a distance of 0.50 m from the nozzle, it can be concluded that droplets are decelerated as a result of air resistance and that smaller droplet sizes slow down more rapidly compared to bigger droplets due to the effect of air drag.

The characteristic time in which the droplet adjusts itself to the sedimentation velocity ($v_{S'}$) is termed relaxation time. This relaxation time is the time in which a particle adjusts itself to an applied force. During the relaxation time, the particle travels a distance known as the stopping distance (D_s), a distance of travel associated with the inertia of the particle. The effects of inertia become significant in situations in which the particle motion is non-uniform, for example, deceleration following ejection from a spray nozzle. The stopping distance D_s (m) can be calculated using formula 1.1 expressed by Bache and Johnstone (1992). Assuming a density of the air ρ_a of 1.24 kg.m^{-3}, a kinematic viscosity of the air υ_a of 1.5×10^{-5} m².s^{-1} and a droplet velocity at the nozzle exit of 17 m.s^{-1} (Thompson & Ley, 1983; Sidahmed *et al*., 1999) a stopping distance of 0.50 m for droplets of about 100 μm is calculated. This corresponds with the distance below the nozzle of the PDPA measurements and the standard boom height above the crop. Logically, droplets smaller than 100 μm in diameter correspond with stopping distances smaller than 0.50 m. A drop released into stationary air accelerates until the aerodynamic drag and gravitational forces are in balance, at which stage the drop will be falling at a uniform velocity, the sedimentation velocity ($v_{S'}$). Using formulas 1.2 and 1.3 (Bache & Johnstone, 1992; Elliott & Wilson, 1983) sedimentation velocities of 0.3 and 0.075 m.s^{-1} are calculated for droplet sizes of 100 and 50 μm.

From Figure 3.17, it is clear that measured droplet velocities are much higher. This demonstrates that the mechanisms of droplet movement under a spray nozzle are very complex and difficult to describe by means of theoretical equations for droplets released in stationary air because of the induced downward air current from the nozzle. This confirms the need for good measuring data. Note that in field conditions, the situation is even more complex with an interaction of the spray with the airflow arising from the induced downward air current from the nozzle, the natural wind conditions and the airflow created by the forward motion of the vehicle.

It is important to know that although a clear correlation between droplet sizes and velocities is found, the variation of droplet velocities within a droplet size interval is high. For our reference nozzle-pressure combination, Hardi ISO F 110 03 at 3.0 bar, standard deviations are indicated in Figure 3.17 by means of error bars. These variations are mainly caused by the fact that droplet velocities are only measured in one direction namely, the vertical dominant direction, while some of the droplets also have a horizontal velocity component because of the shape of the spray cone. This implies that two droplets having the same speed but a different direction, have a different measured vertical velocity. Consequently, three-dimensional droplet velocities would be higher than the measured vertical velocities.

3.3.3.2. Effect of nozzle type

In Figure 3.18, v_{vol50} values are presented for the different Hardi nozzles at a constant pressure of 3.0 bar together with the 95% confidence intervals (t-distribution, $\alpha = 0.05$, df = 8) and in Annex 4 for the v_{vol10}, v_{vol25}, v_{vol75} and v_{vol90} values. A complete overview is presented in Table 3.5.

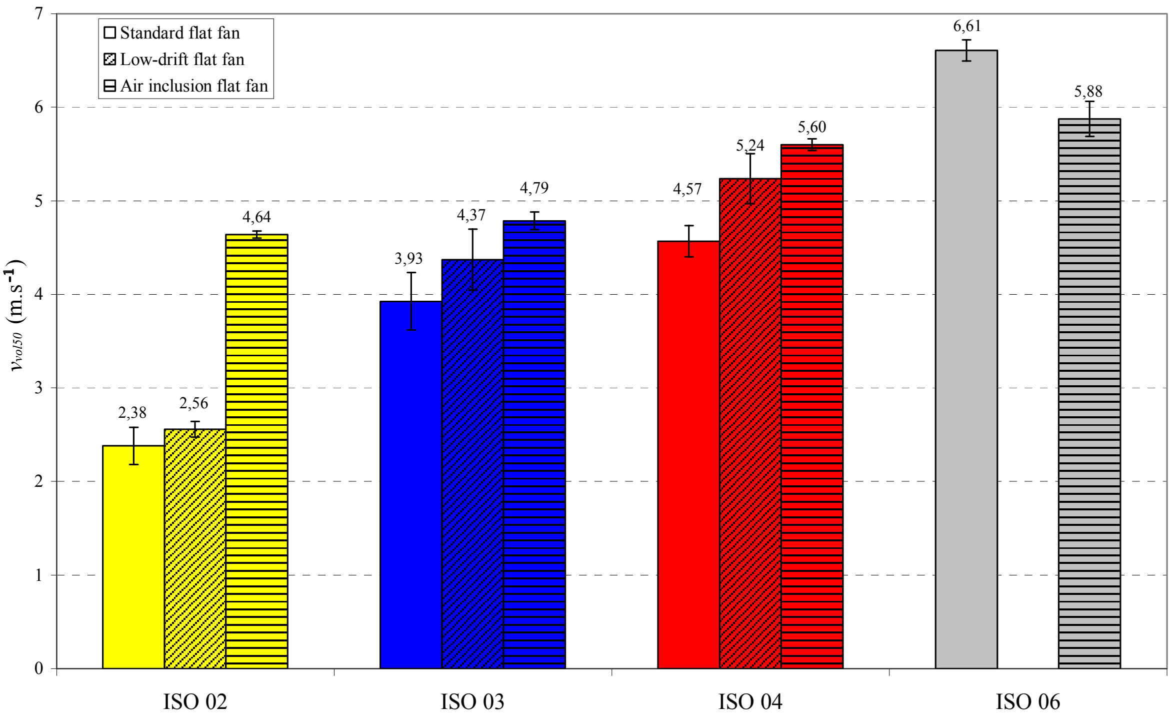

Figure 3.18: Droplet velocity below which slower droplets constitute 50% of the total volume (v_{vol50}) for different Hardi nozzles at a pressure of 3.0 bar together with the 95% confidence intervals

Considering standard flat fan nozzles and low-drift flat fan nozzles, the characteristics v_{vol25}, v_{vol50}, v_{vol75} and v_{vol90} are generally lower for the standard flat fan nozzles compared with the low-drift nozzles for the same nozzle size and pressure but differences are rather limited and only in some cases statistically significant (t-test, $\alpha = 0.05$). On the other hand, v_{vol10} values are significantly lower for the standard flat fan nozzles compared with the low-drift nozzles. For example, at a pressure of 3.0 bar and for ISO 02 nozzle sizes, values for v_{vol10} and v_{vol50} vary from 0.61 and 2.38 m.s^{-1} for the standard flat fan nozzles up to 1.36 and 2.56 m.s^{-1} for the low-drift nozzles.

This can be explained by the fact that droplet velocities and droplet sizes are closely linked, big droplets correspond with high droplet velocities, small droplets with low droplet velocities as described in section 3.3.3.1. Low-drift nozzles have a significantly lower proportion of small droplets and consequently a lower proportion of droplets having a low droplet speed. This correlation between droplet size and velocity is confirmed by Figure 3.19. In this graph, v_{vol50} values are presented for the different Hardi nozzles at 3.0 bar in relation to their corresponding $D_{v0.5}$ values. Similar graphs are presented in Annex 5 for the characteristics v_{vol10} versus $D_{v0.1}$ and v_{vol90} versus $D_{v0.9}$. High $D_{v0.5}$ values correspond with high v_{vol50} values.

Moreover, another clear difference between the three different nozzles types (i.e. standard flat fan, low-drift flat fan and air inclusion nozzles) was observed which cannot be attributed to differences in droplet sizes. Even when droplet size characteristics ($D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$) are equal, droplet velocities vary depending on the nozzle type. For example, no significant difference between droplet size characteristics $D_{v0.1}$ $D_{v0.5}$ and $D_{v0.9}$ of the Hardi ISO F 110 06 nozzles (respectively 176.1, 345.1 and 538.6 µm) and the Hardi ISO LD 110 03 nozzles (respectively 169.8, 348.2 and 509.3 µm) is found but their droplet velocity characteristics v_{vol10}, v_{vol50} and v_{vol90} are significantly different ($\alpha = 0.05$) and, respectively, 1.94, 6.61 and 12.29 m.s^{-1} for the ISO F 110 06 nozzles and 1.06, 4.37 and 9.62 m.s^{-1} for the Hardi ISO LD 110 03. This is illustrated by the differences in intercepts (and slopes) of the first-order regression lines in Figure 3.19. Hence, for the same droplet size and spray pressure, standard flat fan nozzles produce faster droplets than the low-drift flat fan nozzles (Figure 3.17 and Figure 3.19). This is caused by the pre-orifice effect which results in a pressure drop inside the nozzle. Because of this pressure drop, droplet release velocities of a low-drift nozzle are lower compared with the standard flat fan nozzles for a specific droplet size at the same pressure (Miller, 1999). In spite of this, droplet velocity characteristics (e.g. v_{vol10}, v_{vol50} and v_{vol90}) are lower for the flat fan nozzles compared with low-drift nozzles of the same ISO nozzle size (Figure 3.18 and Figure 3.19) because of differences in droplet size characteristics namely, the proportion of small (and slow) droplets is higher for flat fan nozzles compared with low-drift nozzles.

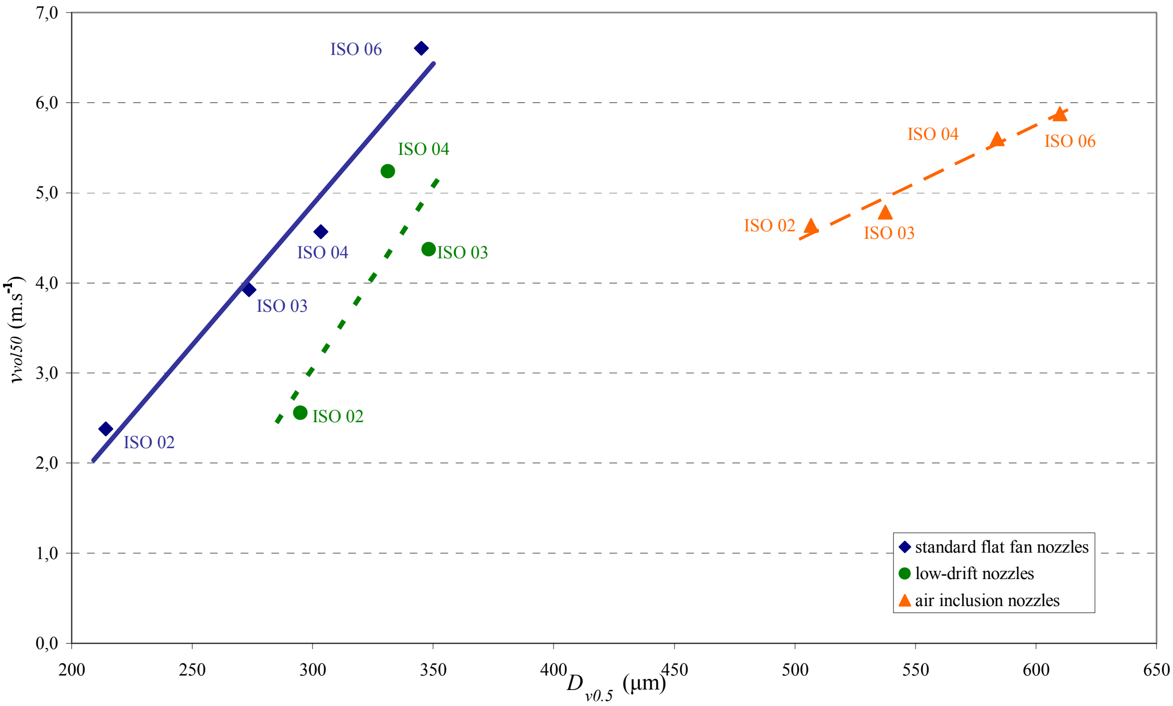

Figure 3.19: Droplet velocities below which slower droplets constitute 50% of the total volume (v_{vol50}) in relation to volume diameters below which smaller droplets constitute 50% of the total spray volume ($D_{v0.5}$) for different Hardi nozzles at a pressure of 3.0 bar

From Figure 3.17, it can be seen that for a given droplet size, corresponding droplet velocities are lowest for air inclusion nozzles compared with standard flat fan or low-drift flat fan nozzles of equal ISO size at the same operating pressure because of the big pressure drop in these nozzles created by a combination of Venturi and pre-orifice effect. The effect of the possible presence of small air bubbles in the droplets, which make them less heavy, is less important because only little air is included using water at a pressure of 3.0 bar (Combellack & Miller, 2001). But again, air inclusion nozzles generally produce sprays with higher droplet velocity characteristics (e.g. v_{vol10}, v_{vol50} and v_{vol90}) compared with standard and low-drift flat fan nozzles of the same size and pressure despite the fact that these nozzles produce the slowest droplets for a given droplet size. Similarly to the low-drift nozzles, this is because very coarse sprays are produced by air inclusion nozzles and the correlation between droplet size and velocities.

The above-mentioned differences in droplet velocity characteristics depending on the nozzle type are also reflected in the *VSF* values, a dimensionless parameter indicative of the uniformity of the drop size velocity distribution. These *VSF* values are presented in Figure 3.20 for the different Hardi nozzles at a pressure of 3.0 bar together with their 95% confidence intervals (t-distribution, α = 0.05, df = 8). Air inclusion nozzles have significantly (α = 0.05) and clearly lower *VSF* values compared to the other nozzles types, representing a much more uniform droplet velocity distribution of the air inclusion nozzles. This can be explained by the relatively high v_{vol10} values (because of the low proportion of small droplets) and the relatively low v_{vol90} values (because of the low ejection velocities). It is illustrated by the steeper curves for air inclusion nozzles in Figure 3.15 and the flatter curves in Figure 3.16. There is a clear tendency that standard flat fan nozzles have higher *VSF* values compared with low-drift flat fan nozzles but differences are much smaller and only statistically significant (t-test, α = 0.05) in case of the ISO 02 nozzles.

In conclusion, droplet velocities at a distance of 0.50 m below the nozzle depend on droplet sizes but also on the ejection velocity at the nozzle. For the same droplet size, droplet velocities are highest for the flat fan nozzles followed by the low-drift nozzles and the air inclusion nozzles. In spite of this, droplet velocities are generally highest for the air inclusion nozzles, followed by the low-drift nozzles and the standard flat fan nozzles for the same nozzle size and spray pressure because of their different droplet size characteristics.

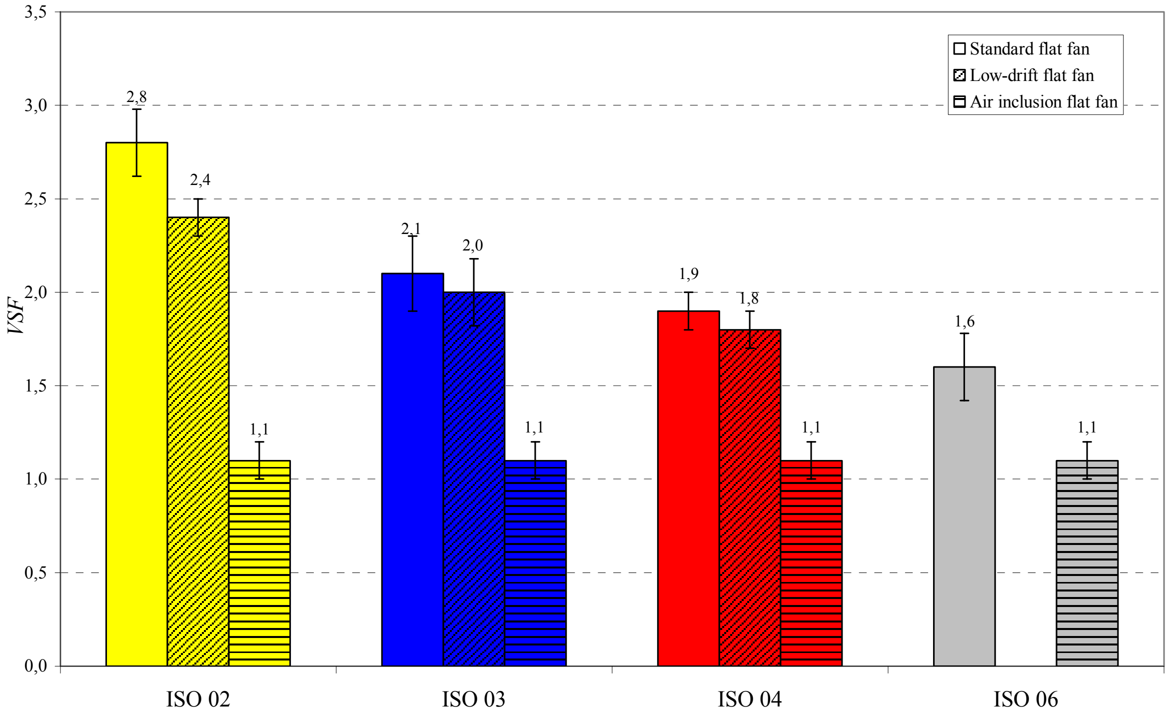

Figure 3.20: Velocity span factors ($VSF = \frac{v_{vol0.9} - v_{vol0.1}}{v_{vol0.5}}$) for the different Hardi nozzle types at a pressure of 3.0 bar together with the 95% confidence intervals

3.3.3.3. Effect of nozzle size

Besides the important effect of nozzle type on the droplet velocity characteristics, there is also an effect of nozzle size (Figure 3.19, Table 3.5). Bigger ISO nozzle sizes correspond with significantly higher droplet velocity characteristics (Figure 3.18, Annex 4 & Annex 5). For example for ISO 02, 03, 04 and 06 Hardi standard flat fan nozzles at a pressure of 3.0 bar, v_{vol50} values were significantly different (t-test, α = 0.05) and respectively, 2.38, 3.93, 4.57 and 6.61 m.s^{-1}. The same conclusion can also be drawn for the other droplet size characteristics (v_{vol10}, v_{vol25}, v_{vol75}, v_{vol75} and v_{vol90}) and for the low-drift and the air inclusion nozzles. Again, this can be explained by the fact that droplet velocities and droplet sizes are closely linked, big droplets correspond with high droplet velocities, small droplets with low droplet velocities. Bigger nozzles have a significantly lower proportion of small droplets and a higher proportion of big droplets for the same nozzle type and spray pressure (§ 3.3.2.2) and consequently a lower proportion of droplets having a low droplet speed and a higher proportion of droplets having a high droplet speed.

Another difference between different sizes of nozzles which cannot be attributed to differences in droplet sizes was found. For one and the same droplet size interval, spray pressure and nozzle type, average droplet velocities vary depending on the ISO nozzle size. This is illustrated in Figure 3.21 for different sizes of low-drift nozzles at a pressure of 3.0 bar and in Annex 6 for the standard flat fan and the air inclusion nozzles. Especially for the low-drift and the standard flat fan nozzles, droplets of the same size are faster for bigger nozzle sizes because of differences in flow resistance. This effect is clearly illustrated in Figure 3.19 where v_{vol50} is significantly higher for the Hardi ISO LD 110 04 nozzles compared with the LD 110 03 nozzles although $D_{v0.5}$ is lower for the LD 110 04 nozzles, as discussed in section 3.3.2.2, with v_{vol50} and $D_{v0.5}$ values of respectively 5.24 and 4.37 m.s^{-1} and 331.2 and 348.2 µm.

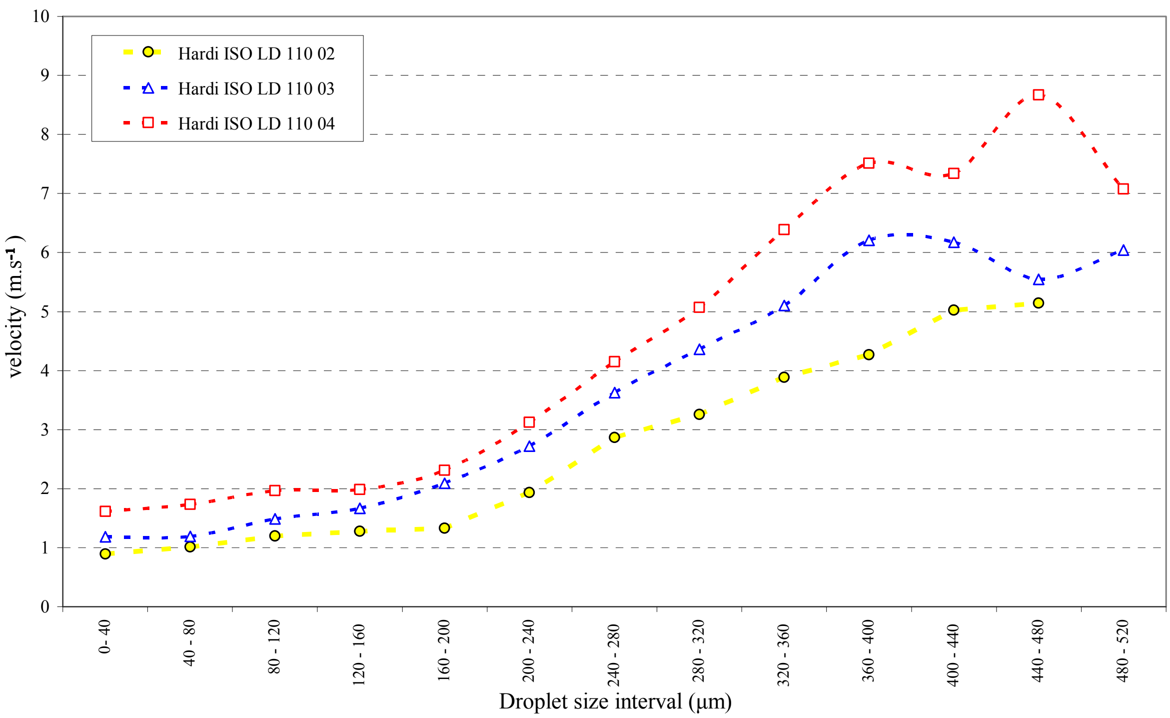

Figure 3.21: Average droplet velocities for the different droplet size classes of different ISO sizes of Hardi ISO LD low-drift nozzles at a pressure of 3.0 bar

For the air inclusion nozzles a similar tendency is found but differences are less clear probably because there is always a big pressure drop in these nozzles created by a combination of Venturi and pre-orifice effect independent from the nozzle size. Again, the above-mentioned differences in droplet velocity characteristics depending on the nozzle size are reflected in the *VSF* values as presented in Figure 3.20. For the standard and the low-drift flat fan nozzles, *VSF* values decrease with increasing nozzle sizes; for the air inclusion nozzles, there is no significant effect of nozzle size on *VSF* values.

In conclusion, the bigger the ISO nozzle size, the higher the droplet velocities at a distance of 0.50 m are for the same nozzle type and spray pressure. This is generally caused by two factors which strengthen each other namely, bigger ISO nozzles produce bigger droplets which are in any case faster. Moreover, droplets of the same size produced by bigger nozzles are faster.

3.3.3.4. Effect of spray pressure

In Figure 3.22, droplet velocity characteristics v_{vol10}, v_{vol25}, v_{vol50}, v_{vol75} and v_{vol90} are presented together with their 95% confidence intervals for the Hardi ISO F 110 03 standard flat fan nozzles at pressures of 2.0, 3.0 and 4.0 bar. In Figure 3.23, the average droplet velocities for the different droplet size classes are shown for the Hardi ISO F 110 03 standard nozzles at pressures of 2.0, 3.0 and 4.0 bar.

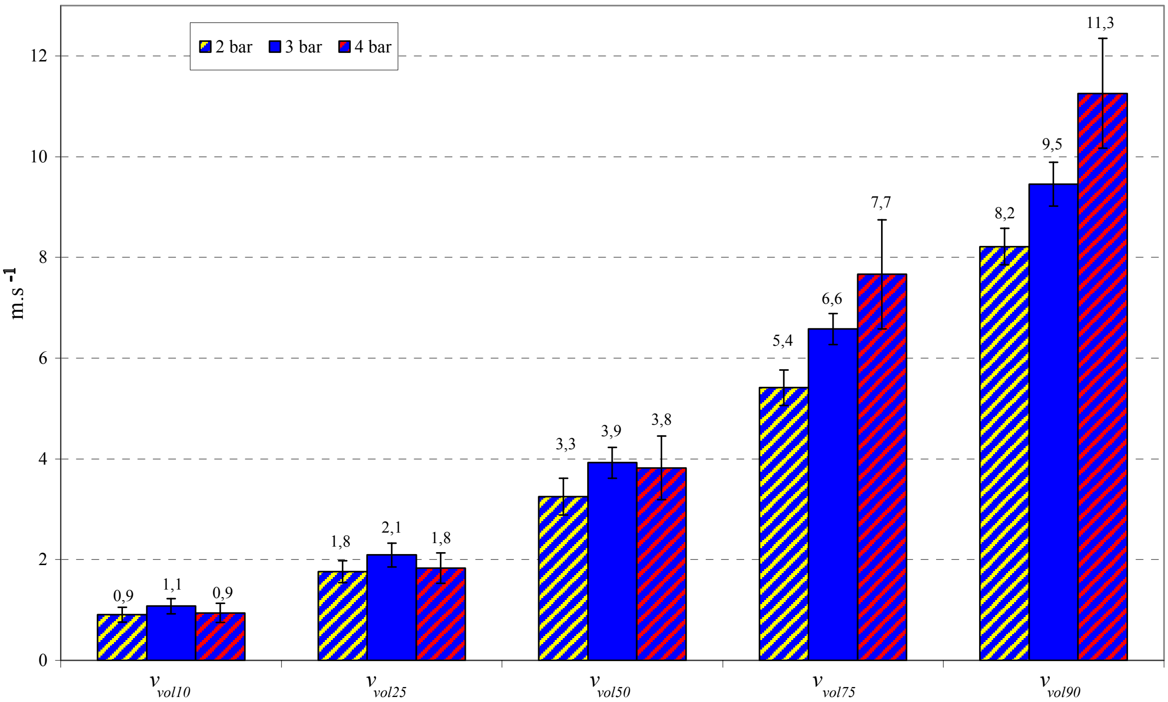

Figure 3.22: Droplet velocities below which slower droplets constitute 10, 25, 50, 75 and 90% of the total volume (v_{vol10}, v_{vol25}, v_{vol50}, v_{vol75} and v_{vol90}) for the Hardi ISO F 110 03 nozzle at pressures of 2.0, 3.0 and 4.0 bar

For the highest droplet velocity characteristics v_{vol75} and v_{vol90}, a significant increase (t-test, $\alpha = 0.05$) is found for increasing spray pressures. For example, values for v_{vol75} increase from 5.4 $m.s^{-1}$ at a pressure of 2.0 bar up to 6.6 $m.s^{-1}$ at a pressure of 3.0 bar and 7.7 $m.s^{-1}$ at a pressure of 4.0 bar. An increase in spray pressure, increases the ejection velocities of the droplets at the exit of the spray nozzle and consequently the droplet velocities measured at 0.50 m from the nozzle for droplets bigger than 200 µm in diameter. This can be explained by the fact that bigger droplets retain their momentum for longer. This is illustrated in Figure 3.23. For the smaller droplets (< 200 µm), there was no effect of variations in spray pressure on their velocities mainly because small droplets have small stopping distances and lose their initial velocity relatively fast as described in section 3.3.3.1.

That is why for the lower droplet velocity characteristics (v_{vol10}, v_{vol25}, v_{vol50}), a similar significant decrease with decreasing spray pressures was only observed for v_{vol50} when the spray pressure was reduced from 3.0 (v_{vol50} = 3.9 $m.s^{-1}$) to 2.0 bar (v_{vol50} = 3.3 $m.s^{-1}$). In all other cases, the effect of spray pressure was not significant within a range from 2.0 to 4.0 bar for the Hardi ISO F 110 03 standard flat fan nozzles. This can be explained on the one hand by the fact that the amount of small droplets slightly increased when the pressure increased (§ 3.3.2.3) and the smaller the droplet size, the lower the droplet velocity at a distance of 0.50 m. On the other hand, the effect of a change of spray pressure on their velocity is less important for smaller droplets at a distance of 0.50 m from the nozzle.
Only in case of raising the spray pressure from 3.0 to 4.0 bar, a significant increase in *VSF* was noted from 2.1 to 2.7 (Table 3.5). There was no significant effect on *VSF* when the pressure was increased from 2.0 to 3.0 bar.

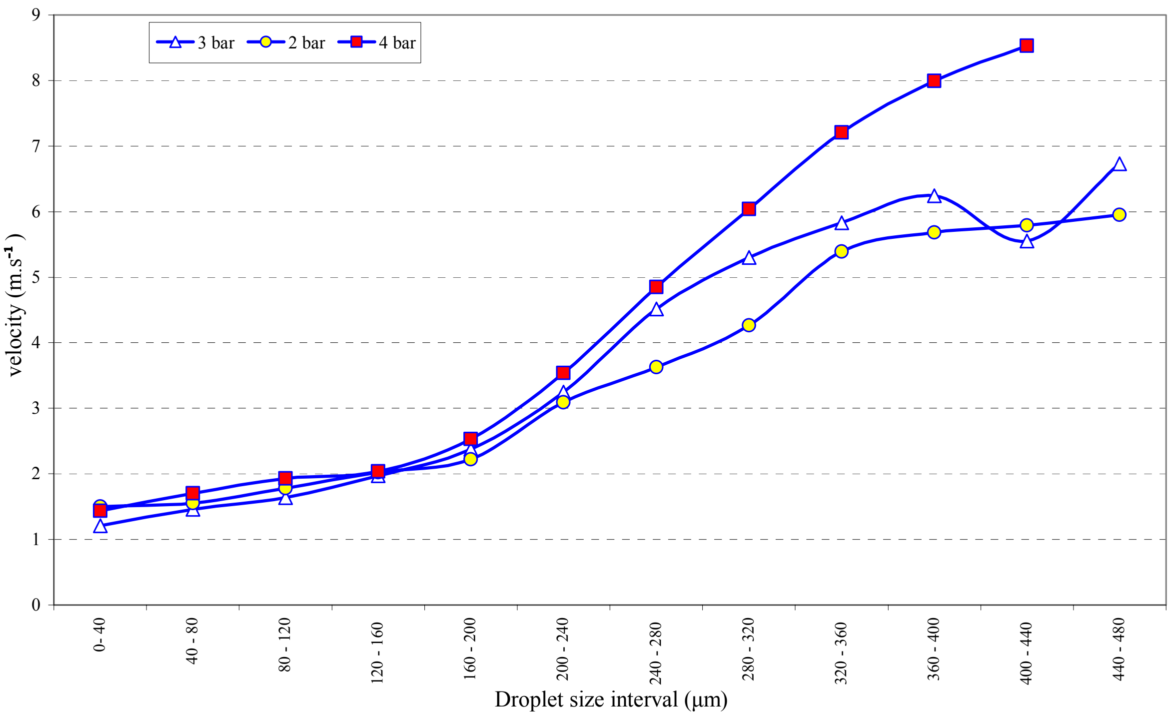

Figure 3.23: Average droplet velocities for different droplet size classes for the Hardi ISO F 110 03 standard flat fan nozzles at pressures of 2.0, 3.0 and 4.0 bar

3.3.4. Comparison with other studies

Different drop size characteristics have already been measured by other researchers using different techniques. For the BCPC reference nozzle-pressure combinations, 17 references ($D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$) were found in total, i.e.: Western *et al*. (1989, Particle Measuring System), Barnett and Matthews (1992, Malvern), Miller *et al*. (1995 b, Dantec PDPA), Hewitt *et al*. (1998, Malvern), Porskamp *et al*. (1999, Aerometrics PDPA), Womac *et al*., (1999, Particle Measuring System, Aerometrics PDPA & Malvern), Nilars *et al*. (2000, Aerometrics PDPA & Particle Measuring System), Womac (2000, Malvern), Herbst (2001 a, Aerometrics PDPA, Malvern & Oxford Laser), Powell *et al*. (2002, Oxford Laser), van de Zande *et al*. (2002 b, Aerometrics PDPA). Different droplet size characteristics (V_{50}, V_{100}, V_{200}, RSF, $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$) resulting from these studies on the BCPC reference nozzle-pressure combinations together with the average values, the 95% confidence intervals and the measuring results from this study are presented in Table 3.6. The spreading of these measurements is presented in Figure 3.24 by means of boxplots together with the PDPA measuring results from this research. It is clear that absolute results differ significantly between different researches depending on measuring protocol, settings, type of measuring equipment and variations in the reference sprays (Womac *et al*., 1999; Womac, 2000). Womac (2000) noted that variations in droplet size characteristics of reference sprays for the same measuring conditions cannot only be attributed to variations in flow rates at a constant pressure. Hence, it is important to use well-defined reference nozzles and not exclusively relying on pressure-flow tolerances. Different types of measuring equipment may result in relative droplet size differences.

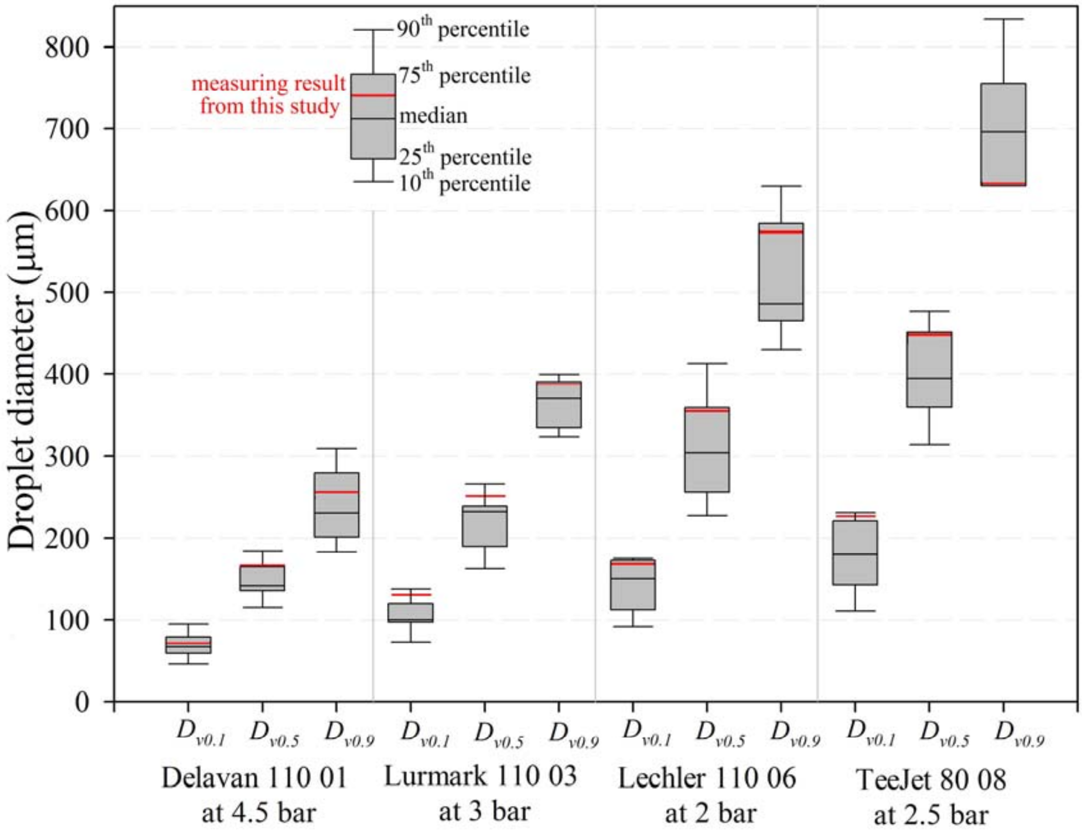

Figure 3.24: Variability of measured results ($D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$) from 17 different studies on four BCPC reference nozzle-pressure combinations by means of boxplots indicating the 10th, 25th, 50th, 75th and 90th percentile of the measuring data and the measuring results from this study with $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ diameters below which smaller droplets constitute 10, 50 and 90 % of the total volume

Table 3.6: Comparison of droplet size characteristics V_{50}, V_{100}, V_{200}, RSF, $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ from 17 different studies on the BCPC reference nozzle-pressure combinations and the measuring results from this study

		Results from this study (average ± sd)	Nilars *et al.*, 2000 (DPPA)	Nilars *et al.*, 2000 (PMS)	Miller *et al.*, 1995 b	Herbst, 2001 a (Malvern)	Herbst, 2001 a (PDPA)	Herbst, 2001 a (Oxford)	Hewitt *et al.*, 1998 (Malvern)	Hewitt *et al.*, 1998 (PDPA)	Womac, 2000 (Malvern)	Womac *et al.*, 1999 (Malvern)	Womac *et al.*, 1999 (PMS)	Womac *et al.*, 1999 (PMS)	Womac *et al.*, 1999 (PDPA)	Western *et al.*, 1989	van de Zande *et al.*, 2002 b	Porskamp *et al.*, 1999	Barnett and Matthews, 1992	BCPC nozzle classification	*Average ± 95 confidence Interval**
Delavan 110 01 – 4.5 bar	V_{50} (%)	**1.9 ± 0.3**										7.8				2.7					*5.3 ± 5.7*
	V_{100} (%)	**18.3 ± 2.4**										40.3	14.2	24.6		18.8		27.9			*25.2 ± 10.0*
	V_{200} (%)	**67.4 ± 3.9**											41.8	40.2							*41.0 ± 1.8*
	RSF	**1.1 ± 0.1**										1.35	1.24	1.53							*1.4 ± 0.2*
	$D_{v0.1}$ (µm)	**79.7 ± 4.3**			100	60	70	75	60	70	43.2	58.6	83	51				63			*66.7 ± 10.5*
	$D_{v0.5}$ (µm)	**165.4 ± 8.0**	139	164	180	134	141	136	140	150	106.9	118.8	188	150.7		141.2		135		182	*147.1 ± 13.2*
	$D_{v0.9}$ (µm)	**263.5 ± 7.5**			270	200	205	200	235	290	175.8	218.4	317.3	282.3				227			*238.3 ± 30.5*
Lurmark F 110 03 – 3 bar	V_{50} (%)	**0.6 ± 0.1**										4.4									
	V_{100} (%)	**5.5 ± 1.2**										24.3					8.8	10.6	18.4		*15.5 ± 8.1*
	V_{200} (%)	**30.8 ± 4.6**																			
	RSF	**1.0 ± 0.1**										1.54									
	$D_{v0.1}$ (µm)	**127.2 ± 10.2**			140	100	105	100	100	120	71.4	76					107	97			*101.6 ± 13.9*
	$D_{v0.5}$ (µm)	**251.0 ± 14.0**	237	238	240	190	213	188	230	235	164.5	160.5					236	221		280	*217.9 ± 21.0*
	$D_{v0.9}$ (µm)	**389.1 ± 20.3**			370	335	350	350	400	395	324.5	323.5					387	390			*362.5 ± 21.0*
Lechler LU120 06 – 2 bar	V_{50} (%)	**0.2 ± 0.0**																			
	V_{100} (%)	**2.7 ± 0.3**																5.4			
	V_{200} (%)	**14.4 ± 1.9**																			
	RSF	**1.1 ± 0.1**																			
	$D_{v0.1}$ (µm)	**170.8 ± 10.7**			160	115	150	110	175	175	91.4							130			*138.3 ± 24.9*
	$D_{v0.5}$ (µm)	**355 ± 10.7**	317	297	290	231	281	226	375	360	247.0							311		429	*305.8 ± 42.4*
	$D_{v0.9}$ (µm)	**573.5 ± 19.5**			475	430	480	455	630	595	485.6							529			*509.9 ± 55.3*
TeeJet 80 08 – 2.5 bar	V_{50} (%)	**0.1 ± 0.0**										0.9									
	V_{100} (%)	**1.2 ± 0.2**										7.2	1.7	4.4				2.9			*4.1 ± 2.7*
	V_{200} (%)	**7.0 ± 1.0**											7.5	9.7							*8.6 ± 2.5*
	RSF	**0.9 ± 0.1**										1.51	1.45	1.52							*1.5 ± 0.0*
	$D_{v0.1}$ (µm)	**231.8 ± 12.5**			190	145	180	140	215	230	103.9	120.9	206.3	167	227			176			*175.1 26.7*
	$D_{v0.5}$ (µm)	**453.0 ± 17.2**	359	253	340	345	361	385	440	450	360.3	368	452.3	408.3	452			404		532	*394.0 ± 38.1*
	$D_{v0.9}$ (µm)	**630.5 ± 7.3**			630	631	632	633	770	740	668.3	695.8	862.7	790.7	736			698			*707.3 ± 48.4*
TeeJet 80 15 – 2 bar	V_{50} (%)	**0.0 ± 0.0**																			
	V_{100} (%)	**0.6 ± 0.1**																2			
	V_{200} (%)	**3.7 ± 0.4**																			
	RSF	**0.8 ± 0.0**																			
	$D_{v0.1}$ (µm)	**292.7 ± 7.1**									126.9							212			*169.5 ± 95.3*
	$D_{v0.5}$ (µm)	**561.8 ± 8.3**									432.1							477		655	*521.4 ± 152.5*
	$D_{v0.9}$ (µm)	**757.4 ± 4.7**									945.1							824			*884.6 ± 135.7*

* Results from this study not included; V_{50}, V_{100}, V_{200}, proportion of total volume of droplets smaller than 50, 100 and 200 µm in diameter; RSF, relative span factor; $D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$, diameter below which smaller droplets constitute 10, 50 and 90% of the total volume

In general, results of the PDPA measurements are situated at the higher end of the spreading. Moreover, variation between measuring results increases with droplet size. This confirms the need for (BCPC) reference nozzle-pressure combinations to classify sprays.

In Table 3.7, the BCPC nozzle classification for the tested nozzle-pressure combinations is compared with the results of five other investigations, also using laser techniques but not considering droplet size class 'extremely coarse'. Despite the relatively wide range of absolute measurements (Figure 3.24), the classification was identical in 72% of the cases. This quite uniform classification confirms the usefulness of these reference nozzles. Within this context, it is important to note that Womac *et al*. (1999) concluded that laser instrument differences may contribute to relative shifts among thresholds for nozzle classification, thereby reducing the precision of uniform nozzle classification. In contrast with droplet size data, information about droplet velocity characteristics is rather rare. Hence, no comparison with other studies was carried out for the droplet velocity results.

Table 3.7: Comparison of BCPC nozzle classification of different Hardi nozzle-pressure combinations from this study with the results from different other investigations

			BCPC nozzle classification from different studies				
Nozzle	**Pressure (bar)**	**Results from this study**	**Hardi nozzles product guide**	**Huygebaert *et al.*, 2004**	**Nilars *et al.*, 2000 (Aerometrics PDPA)**	**Nilars *et al.*, 2000 (PMS)**	**BCPC nozzle card**
Hardi ISO F 110 02	3.0	F	F	F	M	F	F
Hardi ISO F 110 03	4.0	F	M	M			F
Hardi ISO F 110 03	3.0	M	M	M	M	M	F
Hardi ISO F 110 03	2.0	M	M	M			F/M
Hardi ISO F 110 04	3.0	M	M	M	M	M	F/M
Hardi ISO F 110 06	3.0	M	C	C	C	C	M/C
Hardi ISO LD 110 02	3.0	M	M	M	M	M	
Hardi ISO LD 110 03	3.0	M	C	M	M	C	
Hardi ISO LD 110 04	3.0	M	C	C	M	C	
Hardi ISO Injet 110 02	3.0	VC	VC	VC			
Hardi ISO Injet 110 03	3.0	VC	VC	VC			
Hardi ISO Injet 110 04	3.0	EC	VC	VC			
Hardi ISO Injet 110 06	3.0	EC	VC	VC			

VF, very fine; F, fine; M, medium; C, coarse; VC, very coarse; EC, extremely coarse

3.4. Conclusions

The spray quality generated by agricultural nozzles is important considering the efficiency of the pesticide application process because it affects spray deposits, biological efficacy and driftability (Permin *et al.*, 1992; Klein & Johnson, 2002; Wolf, 2002; Taylor *et al.*, 2004). That is why within the framework of this research, a measuring set-up for the characterisation of spray nozzles was developed. This set-up is composed of a controlled climate room, a spray unit, a three-dimensional automated positioning system and an Aerometrics PDPA laser system which measures droplet size and velocity characteristics. As for the PDPA, a droplet passes through a small sampling volume, scattering light by refraction. The frequency of this light is proportional to the droplet velocity and the spatial frequency of the same light is inversely proportional to the droplet diameter. This PDPA is capable of producing huge amounts of useful and repeatable data. A measuring protocol was established prescribing the nozzle selection procedure, the rectangular scan pattern of the spray cloud, the use of a reference nozzle, a measuring height of 0.50 m, constant environmental conditions and the number of measurements for each nozzle-pressure combination. This resulted in a very high repeatability of the measurements. In total, 18 nozzle-pressure combinations were tested corresponding with 162 measurements i.e. the five BCPC reference nozzle-pressure combinations and the 13 Hardi nozzle-pressure combinations tested in this research.

From these measurements, it was found that droplet sizes vary from a few micrometres up to some hundreds of micrometres depending on the nozzle type and size. The five BCPC reference nozzles cover the entire range of measured droplet sizes. Similarly, each nozzle-pressure combination produces a droplet velocity spectrum with velocities varying from about 0 $m.s^{-1}$ up to 16 $m.s^{-1}$. From the results, it is clear that nozzle type as well as nozzle size have an effect on droplet size as well as on droplet velocity characteristics and that there is a relation between droplet size and velocity characteristics.

In general, bigger droplet sizes correspond with higher droplet velocities, small droplets with lower droplet velocities. For the larger droplet sizes (> 400 µm) droplet velocities at 0.50 m from the nozzle exit are relatively constant and vary from about 4.5 up to 8.5 $m.s^{-1}$ depending on the nozzle type and size. Below 400 µm, droplet velocities consistently decrease with the decrease of drop size and also for these smaller droplet sizes, droplet velocities are different for one and the same droplet size interval and vary from 0.5 to 2 $m.s^{-1}$ depending on nozzle size and type. It can be concluded that droplets are decelerated as a result of air resistance and that smaller droplet sizes slow down more rapidly compared to larger droplets due to the effect of air drag. Moreover, mechanisms of droplet movement under a spray nozzle are very complex and difficult to describe which confirms the need for good measuring data.

For the same nozzle size and spray pressure, standard flat fan nozzles produced the finest droplet size spectrum followed by low-drift flat fan nozzles and air injection nozzles. Consequently, significant differences in the proportion of small and drift-prone droplets (V_{100}, V_{200}, etc.) between the different nozzle types were found which is important with regard to driftability. It is noticeable that the effect of nozzle type is more important for smaller ISO nozzle sizes. The important effect of nozzle type on droplet sizes was also reflected in other droplet size characteristics like $D_{v0.5}$, *RSF*, D_{10}, etc. At a pressure of 3.0 bar, all of the standard and the low-drift flat fan nozzles are classified as 'medium', except the ISO 02 standard flat fan nozzle which is classified as 'fine'. The air inclusion nozzles are classified as 'very coarse' for the 02 and 03 ISO nozzle sizes and 'extremely coarse' for the bigger 04 and 06 ISO nozzles sizes.

Droplet velocities at a distance of 0.50 m below the nozzle are determined by the droplet sizes but also by the ejection velocity at the nozzle. For the same droplet size, droplet velocities are highest for the flat fan nozzles followed by the low-drift nozzles and the air inclusion nozzles. This is caused by the pre-orifice effect in case of a low-drift nozzle which results in lower droplet velocities for a specific droplet size at the nozzle exit and by the big pressure drop created by a combination of Venturi and pre-orifice effect in case of air inclusion nozzles. In spite of this, average droplet velocities are generally highest for the air inclusion nozzles, followed by the low-drift nozzles and the standard flat fan nozzles for the same ISO nozzle size and spray pressure because of their different droplet size characteristics and the fact that larger droplet sizes correspond with higher droplet velocities. Hence, it can be concluded that the droplet size effect dominates the ejection velocity effect.

The larger the ISO nozzle size, the coarser is the droplet size spectrum at the same pressure. Consequently, the proportion of small droplets also increases with smaller nozzles and this effect is most important for the standard flat fan nozzles followed by the low-drift flat fan nozzles. For the air inclusion nozzles, the effect of nozzle size on the proportion of small droplets is less important and the proportion of small droplets is low in all the cases. Moreover, bigger ISO nozzle sizes, correspond with higher droplet velocities at a distance of 0.50 m for the same nozzle type and spray pressure. This is caused by two factors which strengthen each other namely, bigger ISO nozzles produce bigger droplets which are in any case faster and droplets of the same size produced by bigger nozzles are faster.

A rather limited series of measurements was carried out to investigate the effect of operating pressure on droplet size characteristics within the limited range from 2.0 to 4.0 bar for the ISO 03 standard flat fan nozzle. From the results, it can be concluded that increasing the spray pressure from 3.0 to 4.0 bar significantly decreases the droplet sizes but the effect is very limited compared to the effect of nozzle size and type. When the pressure was decreased from 3.0 to 2.0 bar, there was no significant effect on droplet size characteristics. This type of nozzle is classified as 'fine' at a pressure of 4.0 bar and as 'medium' at pressures of 2.0 and 3.0 bar. For the droplet velocities at a distance of 0.50 m, only for the fastest droplet velocity characteristics (v_{vol75} and v_{vol90}), a significant decrease was found for decreasing spray pressures. This can be explained by the fact that an increase in spray pressure, increases the ejection velocities of the droplets at the exit of the spray nozzle and consequently the droplet velocities measured at 0.50 m from the nozzle for the bigger droplets (> 200 μm in diameter) because larger droplets retain their momentum longer. For the smaller droplets (< 200 μm), no effect on droplet velocities could be seen when the pressure was increased because small droplets lose their initial velocity relatively fast and because the amount of small droplets slightly increases.

This information is very useful with regard to the risk of spray drift and the quantity and distribution of the deposit on the target. Comparison with the results from other researches confirms the need for reference nozzles to classify sprays because of the considerable variation of absolute results depending on measuring protocol, settings, type of measuring equipment and variations in reference sprays.

Chapter 4 ***Wind tunnel experiments***

4.1. Introduction

Techniques to measure drift and drift potential include those based on field measurements and the use of wind tunnels. Whilst field research (Chapter 5) is appropriate for obtaining realistic estimates of drift with sprayers under a range of working conditions, the controlled conditions of appropriate wind tunnel designs are well suited for relative studies of drift risk.

Wind tunnel experiments provide an efficient method for supporting and complementing the data derived from field experiments alone. They are used to measure airborne and fallout spray volumes and the size and velocities of drifting droplets typically using simplified nozzle mountings in controlled conditions. In addition, wind tunnel studies using single or multiple nozzles mounted on relatively simple structures may also provide suitable methods for measuring and then classifying the performance of nozzle systems independently from that of the sprayer and support vehicle (tractor) on which the nozzle(s) may be mounted and operated (Miller *et al*., 1993). Another major advantage of wind tunnel tests is that experiments to determine the potential of sprays to drift, can be made with different spraying systems under directly comparable and repeatable conditions - in terms of velocity profiles and turbulence levels (Davis, 1987) - in a closely comparable way to actual field conditions. On the other hand, absolute drift values under realistic conditions can only be obtained by means of drift field experiments.

A wind tunnel approach permits the use of a "driftability index", a "relative drift risk factor" or a "drift potential factor" to be developed for current and novel configurations of spraying equipment (Western *et al*. 1989, Miller *et al*., 1989 a; Walklate *et al*., 1994). This information has been used to classify equipment provided to the end user, so that appropriate spraying equipment could be selected to minimize the risk of spray drift (Parkin *et al*., 1994).

In accordance with measurements of droplet characteristics and field-drift measurements, it is increasingly important to unify the different wind tunnel measuring procedures used by different researchers like Miralles and Bogliani (1993), Miller *et al*. (1995 b), Southcombe *et al*. (1997), Phillips & Miller (1999), Herbst and Ganzelmeier (2000) and Walklate *et al*. (2000) as international rules, regulations and commercial trading rapidly develops. At the moment of writing this work, efforts are made to unify wind tunnel measurements for the assessment of spray drift in one international standard method (ISO/DIS 22856, 2007). A complete overview of the state of the art of wind tunnel measurements is given in section 2.3.3.

Wind tunnel experiments were carried out in the Silsoe Research Institute (SRI) wind tunnel facility by the SRI staff in collaboration with Hardi International. This wind tunnel facility has been purpose-built to allow the safe spraying of agricultural pesticides; the appropriate containment and disposal of discharged liquids and airborne droplets being part of its installation. This wind tunnel facility has been used extensively for the drift risk classification of nozzles within the UK's LERAP (§ 2.5.1) and, to a lesser extent, Germany's DIX schemes (§ 2.3.3.1). It is claimed to be the world's most advanced wind tunnel for research into this specialised aspect in the application of agricultural pesticides. The objectives of this chapter were:

- To measure airborne and fallout spray deposits of spray application techniques in a wind tunnel under different conditions,
- To calculate the drift potential of different spray applications using contrasting approaches and to compare the drift potential results with the reference spraying.

In Chapter 6, the relationships between droplet characteristics (Chapter 3), drift potential (Chapter 4) and absolute drift values (Chapter 5) are investigated.

4.2. Materials and Methods

4.2.1. Design and layout of the SRI wind tunnel

Wind tunnel measurements have been carried out in the Silsoe Research Institute wind tunnel facility presented in Figure 4.1. These facilities have been used before by other researchers like Miller *et al*. (1989 a; 1993; 1995 b), Phillips and Miller (1999), Walklate*et al*. (2000) and Taylor *et al*. (2004). This wind tunnel is of a re-circulating design with a working section of 3.0 m wide, 2.0 m high and 7.0 m long. Hence, the wind tunnel is of a sufficient size to permit the spray generator to be used so that the airflow is not disturbed by the proximity of internal walls or the spray generator (or its mounting) and has enough height and downwind distance to contain sufficient arrays of sampling collectors for the calculation of spray drift potential from measurements of downwind spray deposits.

The tunnel produces an approximately uniform laminar upstream flow and a specified air speed range of 0.8 to 8.0 m.s^{-1} but can be effectively used to simulate wind speeds of 0.5 to 10.0 m.s^{-1}. Because the spray sheet being emitted at the nozzle - and the spraying swath with its entrained air - obstructs the flow of wind, it is very likely that vortices are created on the downwind side of the spray nozzle (Farooq *et al*., 2001 b).

Figure 4.1: Picture of the SRI wind tunnel facility

The potential for drift risks of sprays generated by different nozzle designs, pressures, formulations and other factors can be assessed by simulating the range of spraying speeds to which the in-flight spray is to be exposed.

In this study, a single and static nozzle, oriented across the tunnel, was exposed to a wind tunnel air speed from generally 2 $m.s^{-1}$ or 7.2 $km.h^{-1}$ which is in the same order of the reference spraying speed of 8 $km.h^{-1}$ used in the spray drift field measurements. A previous study comparing data derived from different research institutes demonstrated that the agreement between measuring results from different wind tunnel configurations and sampling methodologies was closest for wind speeds in the range from 2.0 to 2.5 $m.s^{-1}$.

Wind speed was constant, without artificially generated turbulence, and was recorded using a sonic anemometer. It must be stressed that the wind speed in the wind tunnel is used to reproduce spraying speeds; in other words, the induced wind speed that is presented to the spraying profile of the nozzle as it moves over the treatment area. In reality, drift generation is very different if there is a crosswind or if the sprayer is being directed into wind or with it. These reproduced conditions are not claimed to take these effects into account but are used to assess **relative** drift risk by determining the quantity of spray that is 'detrained' from the plume; a quantity that would then be available to contribute to the total mass of any drifting cloud. Only few researchers like Smith and Miller (1994) have, so far, performed wind tunnel experiments with a moving nozzle to create two perpendicular components of wind acting on the spray fan. They also demonstrated the importance of nozzle orientation in the wind tunnel and concluded that the spray fan orientated at right angles to the wind direction (which was the case in this study) was a more robust setting than along the winds axis.

4.2.2. Collectors and spray liquid

Spray deposits were measured by sampling or collecting spray displaced by the airflow into a defined downwind area. In this study, nozzle height was generally 0.50 m above the collectors used to predict fallout; corresponding with a height above the floor of 0.60 m since the collectors were suspended 0.10 m above the tunnel's floor to avoid both wind turbulence and contamination (Figure 4.2). The floor of the wind tunnel is designed to minimise any spray liquid splashes or spray droplet bounce using an artificial turf surface. Remark that a nozzle height of 0.50 m is common agricultural practice and was also used as a reference during the PDPA laser measurements (Chapter 3) and the field drift measurements (Chapter 5).

Spray drift risk was assessed by measuring the quantities of spray deposited downwind of the nozzle on horizontal 2 mm diameter polythene lines perpendicular to the wind direction in a vertical and a horizontal array. With these collectors it is possible to sample the passing spray cloud (relatively) non intrusively. They have an acceptable collection efficiency, and dye can be recovered and quantified at reasonable cost with the required resolution and speed. This technique has been used before by many other researchers (Lake *et al*., 1978; Sharp, 1984; Lloyd *et al*., 1986; Gilbert & Bell, 1988; Miller *et al*., 1989 b; Walklate, 1992; Miller & Smith, 1997; Murphy *et al*., 2000; Mathers *et al*., 2000). Six lines - identified as H_1, H_2, H_3, H_4, H_5 and H_6 - were placed in a horizontal array at distances of respectively 2, 3, 4, 5, 6 and 7 m downwind of the nozzle when used at a height of 0.50 m. With these horizontal collecting lines fallout volumes and gradients are determined and data is generated that can be used following schemes such as LERAP (§ 2.5.1).

Five collector lines (V_1 up to V_5) are positioned in a vertical array, with 0.10 m spacing, 2.0 m downwind from the static nozzle - corresponding with nozzle heights of 0.50, 0.40, 0.30, 0.20 and 0.10 m - to totally sample non-intrusively the vertical shape and quantity of the airborne spray cloud. Hence, the heights above the wind tunnel floor of collector lines V_1, V_2, V_3, V_4, and V_5 were, respectively, 0.10, 0.20, 0.30, 0.40 and 0.50 m. These vertical collecting lines are used to determine the airborne spray profile and they provide data when using the DIX scheme (§ 2.3.3.1). Note that collector line H_1 and collector line V_1 are one and the same line. A schematic overview of the setup is presented in Figure 4.2.

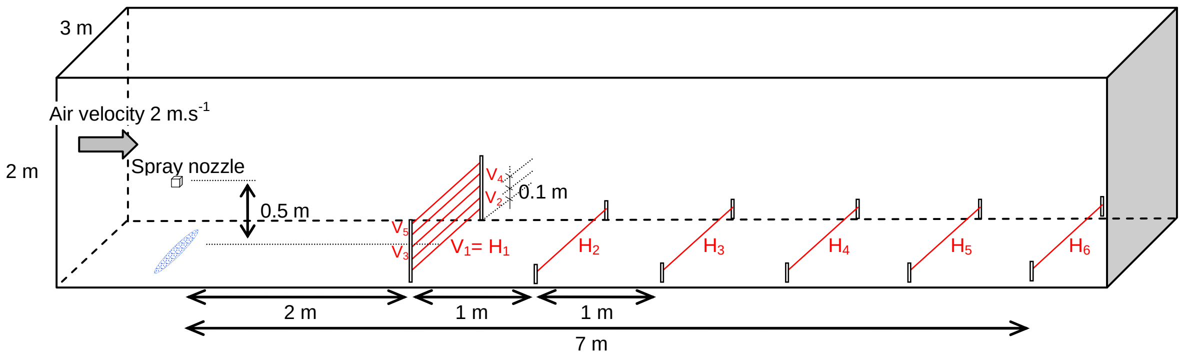

Figure 4.2: Wind tunnel measuring setup with the different collector lines (airborne deposits: $V_1 \rightarrow V_5$ and fallout deposits: $H_1 \rightarrow H_6$)

A water-soluble fluorescent tracer (sodium fluorescein at 0.02%) was dissolved into tap water to permit quantification of the drift deposits recovered from the collecting lines with a Perkin Elmer LS2 filter fluorimeter. This tracer, with a solubility of 600 $g.L^{-1}$, was used before by several researchers (Ford, 1986; Miller *et al.*, 1989 b; Davis *et al.*, 1993; Parkin & Wheeler, 1996; Cross *et al.*, 1997). A non-ionic surfactant (Agral) was added at a volumetric concentration of 0.1% in order to physically simulate a typical spray solution in accordance with the field-drift measurements. The polythene lines were cut to a length of 2.8 m such that they sampled drift from across the full width of its spray plume.

An experimental procedure was set up to avoid spray losses or contamination of the sampled lines. Thus, nozzle emission times were adjusted so that the collectors were not overloaded - nor dripped - at any point across their length. Contamination was avoided by:

- Using a new pair of gloves every time the strings were handled,
- Collectors not touching any contaminated surface before, during or after their use,
- Using new polythene bags and cleaning any apparatus used to quantify the deposits.

After the experiments, the collectors were washed in 250 ml of de-ionised water (+ 0.1% NaOH) and samples of these rinsings were taken. Spray solution samples were also taken at the start and finish of any series of measurements and used to make known concentrations to calibrate the instrument. In Figure 4.3 an inside view of the wind tunnel is presented.

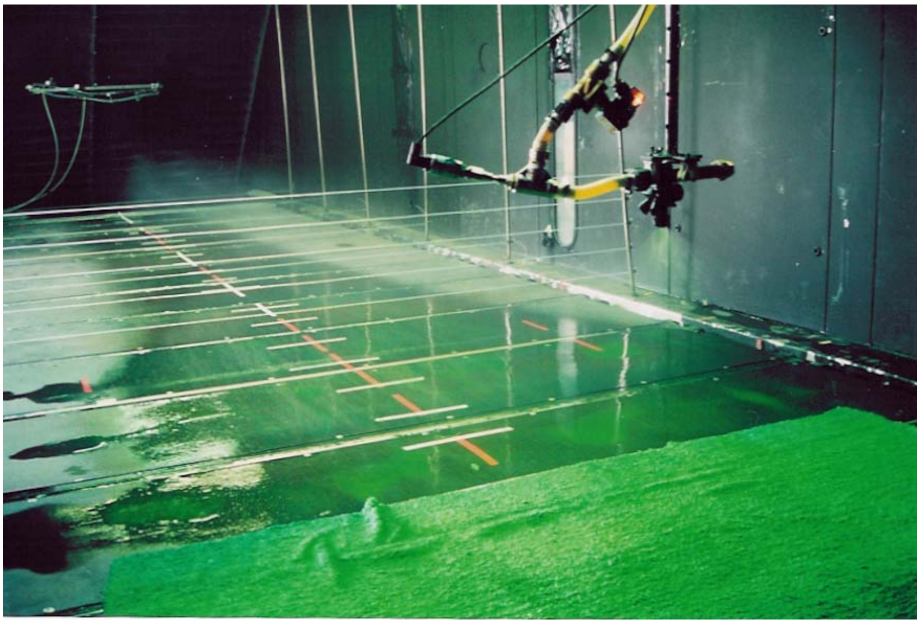

Figure 4.3: Inside view of the SRI wind tunnel with the different collecting lines and the spray nozzle (Taylor *et al.*, 2004)

4.2.3. Measuring protocol

Each nozzle was used individually in the tunnel and was supplied with water from a wheelbarrow sprayer through a pressure indicator and an electronically controlled supply switch. Having set the spray liquid supply system for the correct pressure, a reference electronically controlled exposure of 10 seconds spraying was used for most of the treatments unless otherwise stated. This is a time adequate enough to produce a measurable minimum deposit. This duration should not saturate the lines that have the greatest retained quantities to avoid loss of spray liquid retained on the collectors. However, when very small quantities of spray deposits were being produced (e.g. with the air inclusion nozzles), emission time was increased up to 50 s in a few cases in order to increase the volumes to be read and to reduce variability within data sets.

In addition to liquid flow rate and exposure time, other operating conditions were recorded. Relative humidity in the wind tunnel was controlled to exceed 90% to minimize in-flight evaporation of droplets. Ambient temperature was only registered and relatively constant (about 20°C). In general, nozzle height was 0.50 m above the drift collectors used to predict fallout, only for the reference nozzle pressure combination (Hardi ISO F 110 03 at 3.0 bar) some measurements were done with a nozzle height of 0.70 m in accordance with the field drift measurements. For these measurements, only the horizontal collecting lines (H_1, H_2, H_3, H_4, H_5 and H_6) were brought into account because of the difference in height compared with the other measurements.

The first and last experimental run of each measuring session was performed with the Hardi ISO F 110 03 reference nozzle at 3.0 bar in accordance with the PDPA laser measurements. These values were recorded and used to establish that experimental procedures - for this measuring session - were within acceptable limits or not.

4.2.4. Determination of deposits

Values for deposits have been **normalised** to a common rate of liquid emission by the nozzle and are expressed as the volume of spray recovered from the lines (in µL) for every litre of spray solution that has been emitted by the nozzle. Nozzle output was measured during each experiment. This method enables a direct comparison between nozzles with different flow rates and between experiments with different exposure times. Hence, deposits are expressed as normalised values in $\mu L.L^{-1}$.

4.2.5. Spray application techniques

An overview of the tested spray application techniques is presented in Table 4.1. In total, 51 wind tunnel experiments have been carried out corresponding with 510 deposit measurements including the reference spraying (*rs*) and 13 other spray applications (*os*) identified as experiments *a* up to *m* in Table 4.1. Each spray application is defined by the nozzle type (standard flat fan, low-drift flat fan and air inclusion) and size (ISO 02, 03, 04 and 06), the spray pressure (2.0 and 3.0 bar), the nozzle height (0.50 and 0.70 m) and the wind speed (2 and 5 $m.s^{-1}$). These spray application techniques were also tested with the PDPA laser (Chapter 4) and in the field (Chapter 6). For the wind tunnel experiments, the reference spraying (*rs*) is defined as a Hardi ISO F 110 03 standard flat fan nozzle at 3.0 bar with a nozzle height of 0.50 m at a wind speed of 2 $m.s^{-1}$ and corresponds with the reference spraying with the PDPA laser and in the field. This reference spraying is used for a comparative assessment of the different spray applications.

Table 4.1: Overview of the tested spray applications in the wind tunnel

Experiment	Nozzle	Pressure (bar)	Nozzle height (m)	Flow rate[b] ($L.min^{-1}$)	Exposure time (s)	Wind speed ($m.s^{-1}$)	Number of repetitions
a 1	Hardi ISO F 110 02	3.0	0.50	0.80	10	2	1
b 1	Hardi ISO F 110 02	3.0	0.50	0.80	10	5	1
c 1-3	Hardi ISO F 110 03	2.0	0.50	0.98	10	2	3
rs 1-18	Hardi ISO F110 03[a]	3.0	0.50	1.20	10	2	18
d 1	Hardi ISO F110 03[a]	3.0	0.50	1.20	10	5	1
e 1	Hardi ISO F110 03	3.0	0.70	1.20	10	2	1
f 1-3	Hardi ISO F 110 04	3.0	0.50	1.60	10	2	3
g 1-2	Hardi ISO F 110 06	3.0	0.50	2.40	10	2	2
h 1-4	Hardi ISO LD 110 02	3.0	0.50	0.80	10	2	4
i 1-3	Hardi ISO LD 110 03	3.0	0.50	1.20	10	2	3
j 1-3	Hardi ISO LD 110 04	3.0	0.50	1.60	10	2	3
k 1-5	Hardi ISO Injet 110 02	3.0	0.50	0.80	10 & 50[c]	2	5
l 1-3	Hardi ISO Injet 110 03	3.0	0.50	1.20	10 & 50[d]	2	3
m 1-3	Hardi ISO Injet 110 04	3.0	0.50	1.60	10	2	3
						Total	**51**

[a] Reference spray application; [b] Nominal flow rate; [c] Two tests with an exposure time of 10 s and three tests with an exposure time of 50 s; [d] Two tests with an exposure time of 10 s and one test with an exposure time of 50 s; F, Hardi ISO 110 standard flat fan nozzles; LD, Hardi ISO 110 low-drift nozzles; Injet, Hardi ISO Injet air inclusion nozzles

4.3. Results and discussion

4.3.1. Fallout and airborne deposit results

A complete overview of the deposit measurements of the 51 wind tunnel experiments can be found in Annex 7. Average fallout deposit results from the 14 different spray applications (Table 4.1) are presented in Table 4.2 together with their standard deviations in case of repetitions. Airborne deposit results were not considered in case of an increased nozzle height (experiment *e*) which resulted in 13 spray application techniques as presented in a similar way in Table 4.3. Fallout and airborne deposit results are also presented graphically in Annex 8 both with a logarithmic and linear scale of the deposit axis. The magnitude of deposits recovered from collector lines, can vary for one and the same nozzle-pressure combination for reasons attributable to the tunnel, analysis and/or operator skills and changes in nozzle performance.

Table 4.2: Average fallout deposit results (± sd) of the 14 spray applications tested in the wind tunnel with collector lines H_1, H_2, H_3, H_4, H_5 and H_6 at distances of respectively 2, 3, 4, 5, 6 and 7 m downwind of the nozzle

Nozzle	Pressure (bar)	Nozzle height (m)	Flow rate[b] (L.min^{-1})	Wind speed (m.s^{-1})	Fallout deposit results (μL.L^{-1})					
					H_1	H_2	H_3	H_4	H_5	H_6
F 110 02	3.0	0.50	0.80	2	948.8	210.8	110.9	61.7	45.5	34.5
F 110 02	3.0	0.50	0.80	5	1767.0	1164.0	948.8	779.9	677.8	555.2
F 110 03	2.0	0.50	0.98	2	563.5 ± 20.1	220.7 ± 25.8	103.7 ± 12.0	52.6 ± 12.2	42.4 ± 6.9	24.5 ± 4.0
F110 03[a]	3.0	0.50	1.20	2	535.4 ± 115.9	128.2 ± 20.0	63.0 ± 11.6	37.6 ± 7.8	26.1 ± 3.7	19.3 ± 4.6
F110 03[a]	3.0	0.50	1.20	5	1214.3	772.4	595.1	481.8	429.6	362.6
F110 03	3.0	0.70	1.20	2	835.0	425.0	200.0	105.0	65.0	40.0
F 110 04	3.0	0.50	1.60	2	273.5 ± 24.7	67.6 ± 11.0	30.4 ± 4.7	20.5 ± 5.3	14.1 ± 2.7	10.7 ± 1.6
F 110 06	3.0	0.50	2.40	2	139.3 ± 57.8	34.2 ± 8.1	17.8 ± 3.2	11.0 ± 2.0	6.9 ± 1.7	4.9 ± 1.8
LD 110 02	3.0	0.50	0.80	2	376.6 ± 52.8	173.8 ± 40.2	81.7 ± 25.1	45.4 ± 22.9	33.1 ± 19.5	25.2 ± 13.1
LD 110 03	3.0	0.50	1.20	2	311.7 ± 47.1	102.6 ± 17.2	46.0 ± 1.9	28.3 ± 2.0	20.0 ± 1.9	15.1 ± 1.9
LD 110 04	3.0	0.50	1.60	2	312.9 ± 100.8	80.1 ± 25.9	37.2 ± 8.8	21.4 ± 4.1	13.3 ± 2.5	9.6 ± 1.4
Injet 110 02	3.0	0.50	0.80	2	40.3 ± 9.3	22.5 ± 4.1	11.4 ± 3.9	6.7 ± 5.6	5.1 ± 4.5	4.5 ± 3.9
Injet 110 03	3.0	0.50	1.20	2	25.9 ± 5.5	12.9 ± 2.7	5.1 ± 5.2	2.7 ± 2.6	2.4 ± 2.6	2.1 ± 2.7
Injet 110 04	3.0	0.50	1.60	2	35.1 ± 3.5	17.7 ± 2.9	7.4 ± 4.0	5.0 ± 2.5	2.1 ± 2.0	3.1 ± 1.3

[a] Reference spray application; [b] Nominal flow rate; F, Hardi ISO 110 standard flat fan nozzles; LD, Hardi ISO 110 low-drift nozzles; Injet, Hardi ISO Injet air inclusion nozzles

Table 4.3: Average airborne deposit results (± sd) of the 13 spray applications tested in the wind tunnel with collector lines V_1, V_2, V_3, V_4, and V_5 at two metres distance from the nozzle corresponding with nozzle heights of 0.50, 0.40, 0.30, 0.20 and 0.10 m

Nozzle	Pressure (bar)	Nozzle height (m)	Flow rate[b] (L.min^{-1})	Wind speed (m.s^{-1})	Airborne deposit results (µL.L^{-1})				
					V_1	V_2	V_3	V_4	V_5
F 110 02	3.0	0.50	0.80	2	948.8	179.9	16.2	6.6	5.9
F 110 02	3.0	0.50	0.80	5	1767.0	1645.8	1319.7	777.7	247.5
F 110 03	2.0	0.50	0.98	2	563.5 ± 20.1	385.5 ± 95.0	68.9 ± 23.2	3.5 ± 3.2	1.4 ± 1.3
F110 03[a]	3.0	0.50	1.20	2	535.4 ± 115.9	146.3 ± 59.4	14.5 ± 8.5	2.4 ± 2.8	2.7 ± 3.3
F110 03[a]	3.0	0.50	1.20	5	1214.3	1179.3	810.3	519.2	118.7
F 110 04	3.0	0.50	1.60	2	273.5 ± 24.7	42.8 ± 9.1	1.5 ± 15	0.5 ± 0.9	0.4 ± 0.7
F 110 06	3.0	0.50	2.40	2	139.3 ± 57.8	28.9 ± 8.0	6.0 ± 7.0	1.8 ± 2.5	0.6 ± 0.9
LD 110 02	3.0	0.50	0.80	2	376.6 ± 52.8	288.3 ± 36.4	115.1 ± 22.5	11.2 ± 7.9	4.3 ± 6.3
LD 110 03	3.0	0.50	1.20	2	311.7 ± 47.1	178.0 ± 56.5	35.0 ± 14.7	4.2 ± 5.2	2.2 ± 3.3
LD 110 04	3.0	0.50	1.60	2	312.9 ± 100.8	143.2 ± 88.2	12.8 ± 7.5	1.8 ± 1.7	2.6 ± 2.2
Injet 110 02	3.0	0.50	0.80	2	40.3 ± 9.3	33.8 ± 6.6	13.6 ± 6.0	3.5 ± 3.9	2.7 ± 3.1
Injet 110 03	3.0	0.50	1.20	2	25.9 ± 5.5	18.0 ± 2.8	5.4 ± 5.2	1.8 ± 2.9	1.8 ± 2.9
Injet 110 04	3.0	0.50	1.60	2	35.1 ± 3.5	26.3 ± 5.1	10.5 ± 7.9	0.1 ± 0.1	0.0 ± 0.0

[a] Reference spray application; [b] Nominal flow rate; F, Hardi ISO 110 standard flat fan nozzles; LD, Hardi ISO 110 low-drift nozzles; Injet, Hardi ISO Injet air inclusion nozzles

4.3.2. Drift potential factor and drift potential reduction percentage

Different studies showed that fallout and airborne deposit results can be used to calculate a *relative drift risk factor* or a *drift potential* (*DP*) for the different spray applications as described in detail in section 2.3.3.1. This drift potential expresses the relative (rather than the absolute) quantity of spray liquid that is potentially carried out of the sprayed (treated) area by the action of air currents during the application process. In this thesis, three different approaches were followed to calculate drift potential:

1. To establish a comparative scale based on the calculation of the first moment of the airborne spray profile measured at a distance of 2.0 metres downwind of the nozzle based on airborne spray deposits from collector lines V_1 up to V_5 as proposed by Miller *et al*. (1989 a) and Southcombe *et al*. (1997). This approach accounts for conditions where total airborne spray volumes from two nozzle systems are similar but with one system giving the airborne spray at a greater height which, under field

conditions, would then be more susceptible to drift (Castell, 1993). A similar approach was followed among others by Herbst and Helck (1998), Herbst and Ganzelmeier (2000) and Herbst (2001 b) who were following the DIX scheme (§ 2.3.3.1). This drift potential (DP_{V1}) is calculated as follows:

$$DP_{V1} = \sum_{i=1}^{5} V_i . h_i \tag{4.1}$$

With

DP_{V1} – drift potential based on calculation of the first moment of the airborne deposit profile (µL.m.L^{-1}),
V_i – airborne deposit result at collector line V_i (µL.L^{-1}),
h_i – height above the floor, respectively, 0.10, 0.20, 0.30, 0.40 and 0.50 m for *i* values of 1, 2, 3, 4 and 5.

2. To calculate the surface under the measured airborne deposit curve by means of numerical integration based on the results from collector lines V_1 up to V_5. This approach only accounts for the total amount of airborne spray volumes. Hence, this drift potential (DP_{V2}) is calculated as follows:

$$DP_{V2} = \sum_{i=1}^{5} V_i . \Delta h_i \tag{4.2}$$

With

DP_{V2} – drift potential based on numerical integration of the airborne deposit curve (µL.m.L^{-1}),
V_i – airborne deposit result at collector line V_i (µL.L^{-1}),
Δh_i – height interval corresponding with collector line V_i, respectively, 0.05, 0.10, 0.10, 0.10 and 0.05 m for *i* values of 1, 2, 3, 4 and 5.

3. To calculate the surface under the measured fallout deposit curve by means of numerical integration based on the results from collector lines H_1 up to H_6. A similar approach was followed by Taylor *et al*. (1999) and Nilars (2002). This drift potential (DP_H) is calculated as follows:

$$DP_H = \sum_{i=1}^{6} H_i . \Delta x_i \tag{4.3}$$

With

DP_H – drift potential based on numerical integration of the fallout deposit curve (µL.m.L^{-1}),
H_i – fallout deposit result at collector line H_i (µL.L^{-1}),
Δx_i – distance interval corresponding with collector line H_i, respectively, 0.5, 1.0, 1.0, 1.0 and 1.0 and 0.5 m for *i* values of 1, 2, 3, 4, 5 and 6.

Drift potential values of the different other sprayings (*os*) are compared with the equivalent results obtained from reference spraying (*rs*) by calculating their drift potential reduction percentage (*DPRP*, %). The *DPRP* of these other sprayings is expressed as the percentage reduction of their drift potential compared with the reference spraying. These *DPRP* values are calculated by comparing the drift potential values of these other sprayings (DP^{os}) with the drift potential of the reference spraying (DP^{rs}) using the following formula:

$$DPRP = \frac{(DP^{rs} - DP^{os})}{DP^{rs}}.100 \qquad (4.4)$$

With

$DPRP$ – drift potential reduction percentage (%),
DP^{rs} – drift potential of the reference spraying (µL.m.L^{-1}),
DP^{os} – drift potential of one of the other sprayings (µL.m.L^{-1}).

$DPRP$ values are calculated following the three different approaches resulting in $DPRP_{V1}$ and $DPRP_{V2}$ values based on airborne spray deposits, and $DPRP_H$ values, based on fallout spray deposits. These results are further discussed below.

Table 4.4: $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$ values (± sd) of the spray applications tested in the wind tunnel at a wind speed of 2 m.s^{-1}

Nozzle	Pressure (bar)	Nozzle height (m)	$DPRP_{V1}$ (%)		$DPRP_{V2}$ (%)		$DPRP_H$ (%)	
			average	*sd*	average	*sd*	average	*sd*
F 110 02	3.0	0.50	- 57.9	/	- 54.6	/	-73.0	/
F 110 03	2.0	0.50	-74.6	*31.1*	-48.4	*18.2*	-34.1	*7.4*
F110 03[a]	3.0	0.50	0.0	*25.2*	0.0	*21.1*	0.0	*14.4*
F110 03	3.0	0.70	not applicable		not applicable		-131.6	/
F 110 04	3.0	0.50	58.9	*4.3*	53.8	*4.8*	48.4	*6.2*
F 110 06	3.0	0.50	74.8	*12.2*	74.8	*10.3*	73.3	*8.4*
LD 110 02	3.0	0.50	-52.5	*28.3*	-14.6	*17.7*	-0.5	*26.4*
LD 110 03	3.0	0.50	10.6	*18.2*	24.1	*15.9*	32.3	*7.0*
LD 110 04	3.0	0.50	6.5	*34.3*	33.0	*27.5*	41.1	*16.6*
Injet 110 02	3.0	0.50	80.3	*7.3*	86.8	*3.1*	87.3	*4.2*
Injet 110 03	3.0	0.50	89.4	*5.7*	92.5	*2.1*	93.0	*3.2*
Injet 110 04	3.0	0.50	86.6	*4.1*	89.4	*2.3*	90.4	*2.1*

[a] Reference spray application; F, Hardi ISO 110 standard flat fan nozzles; LD, Hardi ISO 110 low-drift nozzles; Injet, Hardi ISO Injet air inclusion nozzles; *DPRP*, Drift potential reduction percentage

4.3.3. Effect of nozzle type

Average fallout wind tunnel deposit results at a wind speed of 2 m.s^{-1} of different nozzle types (standard flat fan nozzles, low-drift flat fan nozzles and air inclusion nozzles) and sizes (ISO 02, 03 and 04) at a spray pressure of 3.0 bar are given in Figure 4.4. Remember the reference spray application was defined as a Hardi ISO F 110 03 standard flat fan nozzle at a pressure of 3.0 bar with a nozzle height of 0.50 m. The results show the expected fallout profiles with the highest deposits closest to the nozzle and a systematic decrease with distance from the nozzle.
Airborne results, for the same nozzle-pressure combinations and conditions, are shown in Figure 4.5 with a logarithmic scale of the X-axis. For the airborne deposit profiles, the

highest deposits are found at the lowest collectors with an important systematic decrease with increasing heights above the tunnel's floor. These results are based on experiments *a1*, *c 1-3*, *rs 1-18*, *e 1*, *f 1-3*, *h 1-4*, *i 1-3*, *j 1-3*, *k 1-4*, *l 1-3* and *m 1-3* as described in Table 4.1 and are presented in more detail in Table 4.2, Table 4.3 and Annex 7.

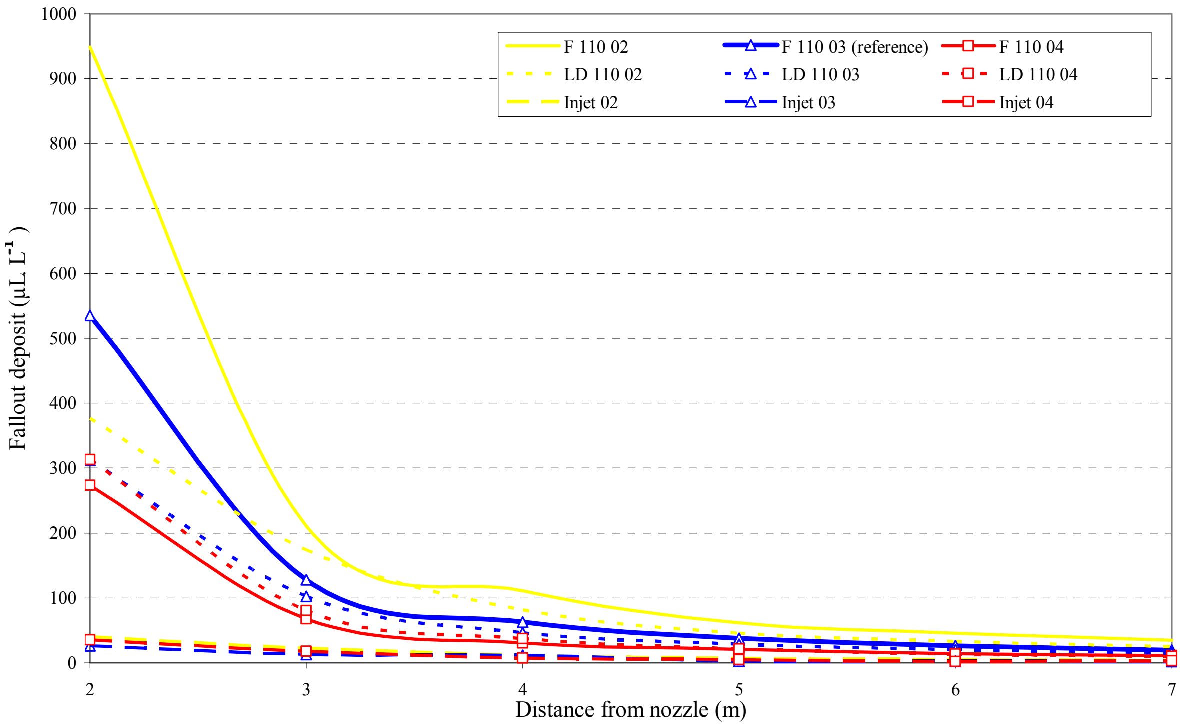

Figure 4.4: Average fallout wind tunnel deposits for different Hardi ISO nozzle types and sizes at a spray pressure of 3.0 bar and a wind speed of 2 m.s^{-1}

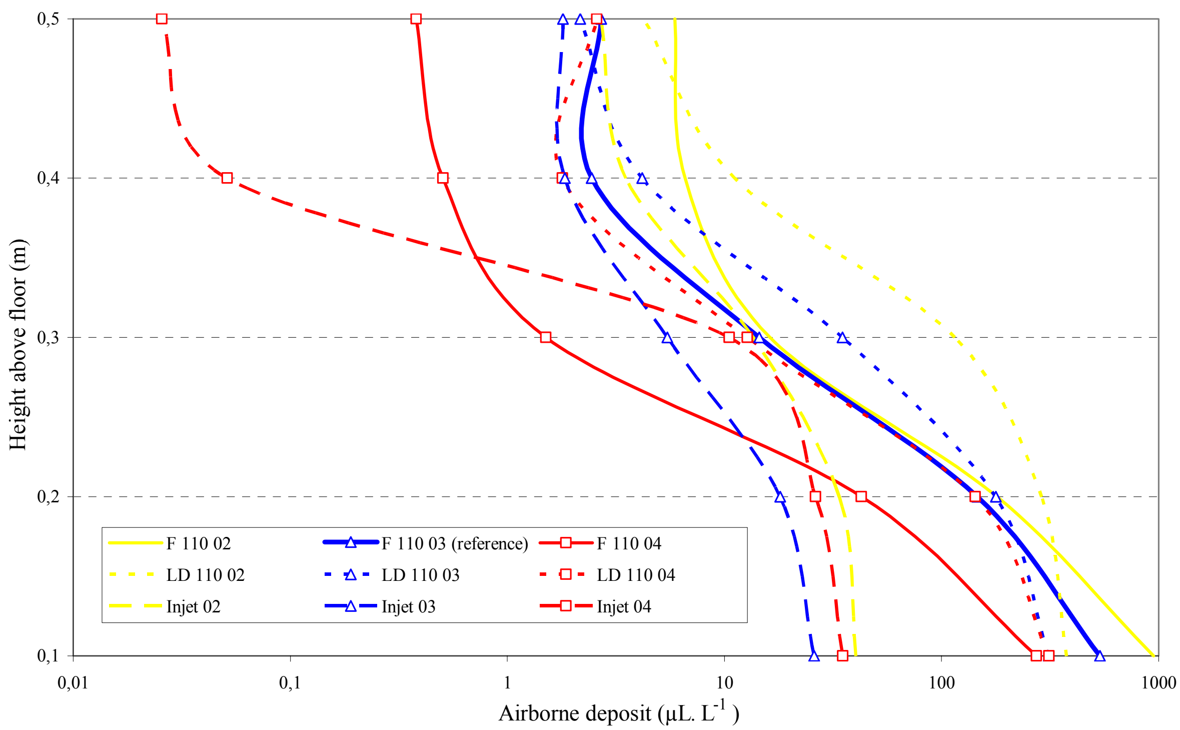

Figure 4.5: Average airborne wind tunnel deposits for different Hardi ISO nozzle types and sizes at a spray pressure of 3.0 bar and a wind speed of 2 m.s^{-1} with a logarithmic scale of the deposit axis

Based on these deposit measurements, drift potential reduction percentages $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$ are calculated as described in section 4.3.2 and presented in Figure 4.6 together with their 95% confidence intervals (t-distribution) in case of more than one repetition. It is clear that the nozzle type has an important influence on the drift potential for the ISO 02 as well as for the ISO 03 and 04 nozzle sizes (Figure 4.6). For one and the same nozzle size, *DPRP* values of the air inclusion nozzles are always higher than *DPRP* values of the standard flat fan and the low-drift flat fan nozzles and differences are statistically significant (α = 0.05, t-test). Hence, air inclusion nozzles offer the greatest scope for reduction of airborne and fallout deposits by the nozzle alone.

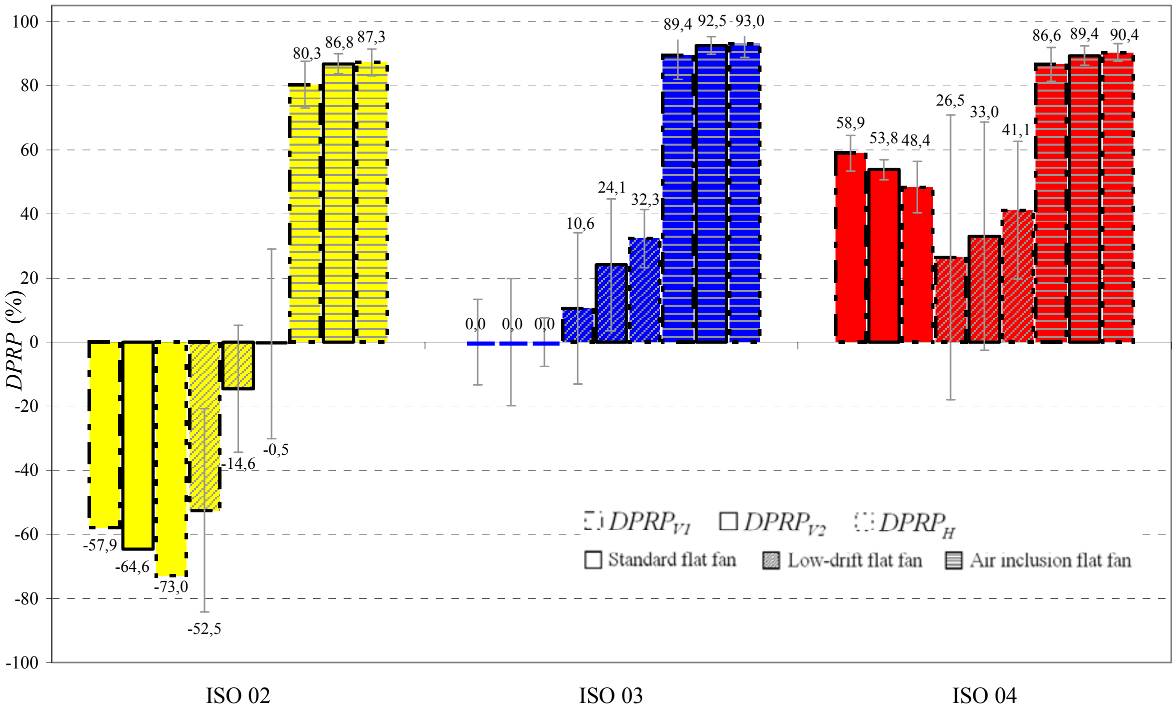

Figure 4.6: $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$ values and their 95% confidence intervals for different Hardi ISO nozzle types (and sizes) compared to the reference (Hardi ISO F 110 03 standard flat fan) at a pressure of 3.0 bar

In case of ISO 02 and ISO 03 nozzle sizes, low-drift nozzles have higher *DPRP* values compared with standard flat fan nozzles. For example, for an ISO 02 nozzle size, $DPRP_{V2}$ values are -64.4% for the standard flat fan nozzles, -14.6% for the low-drift nozzles and 86.8% for the air injection nozzles. Similar tendencies were found for $DPRP_{V1}$ and $DPRP_H$ values and for the ISO 03 nozzle sizes. The fact that *DPRP* values are higher for low-drift nozzles compared with standard nozzles could only be proved statistically (t-test, α = 0.05) in case of $DPRP_H$ for the ISO 03 nozzles mainly because of the limited number of repetitions. $DPRP_H$ values of 0.0 ± 14.4% (reference spraying) and 32.3 ± 7.0% were found, respectively, for the standard and the low-drift ISO 03 nozzles.

For the ISO 04 nozzle sizes, there was no statistically significant difference (t-test, α = 0.05) between $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$ values of the standard flat fan and the low-drift flat fan nozzles and *DPRP* values even tended to be lower for the low-drift nozzles. For example, $DPRP_{V2}$ values were 53.8%, 33.0% and 89.4%, respectively, for the ISO 04 standard, low-drift and air inclusion nozzles. A similar tendency was found for the $DPRP_{V1}$ and $DPRP_H$ values.

In conclusion, for the same nozzle size and spray pressure, the drift potential (expressed by *DPRP* values) is generally higher for the air inclusion nozzles followed by the low-drift nozzles and the standard flat fan nozzles. The effect of nozzle type is most important for smaller nozzle sizes. Other researchers (e.g. Walklate *et al*., 1994) confirmed that low-drift nozzles and air inclusion nozzles can reduce downwind deposits compared with conventional standard flat fan nozzles. Only in case of the ISO 04 standard and low-drift flat fan nozzles, this tendency was not followed and in some cases differences were not statistically significant because of the limited number of repetitions and/or the variation between the measuring results.

4.3.4. Effect of nozzle size

Average fallout wind tunnel deposit results of different nozzle sizes (ISO 02, 03, 04 and 06) and types (standard flat fan nozzles, low-drift flat fan nozzles and air inclusion nozzles) at a spray pressure of 3.0 bar are presented in Figure 4.7 with a logarithmic scale of the Y-axis. For the same nozzle-pressure combinations, airborne deposit results are presented in Figure 4.8. These results are based on experiments *a1*, *c 1-3*, *rs 1-18*, *e 1*, *f 1-3*, *g 1-2*, *h 1-4*, *i 1-3*, *j 1-3*, *k 1-4*, *l 1-3* and *m 1-3* as described in Table 4.1 and are presented in more detail in Table 4.2, Table 4.3 and annex 7.

Drift potential reduction percentages $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_{H}$ for the different nozzle-pressure combinations are presented in Figure 4.9 together with the 95% confidence intervals based on the airborne and fallout deposit measurements.
From these graphs, it is clear that besides nozzle type, the size of the nozzle is also related to the drift potential.

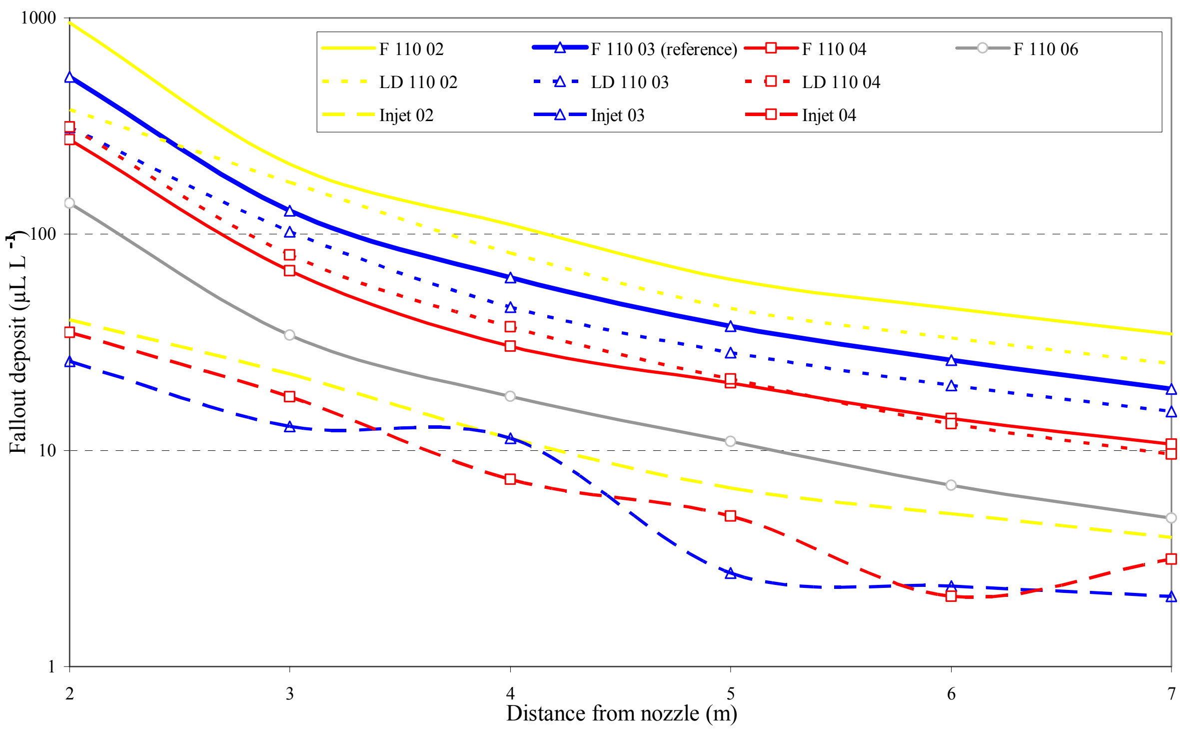

Figure 4.7: Average fallout wind tunnel deposits for different Hardi ISO nozzle sizes and types at a spray pressure of 3.0 bar and a wind speed of 2 m.s^{-1} with a logarithmic scale of the Y-axis

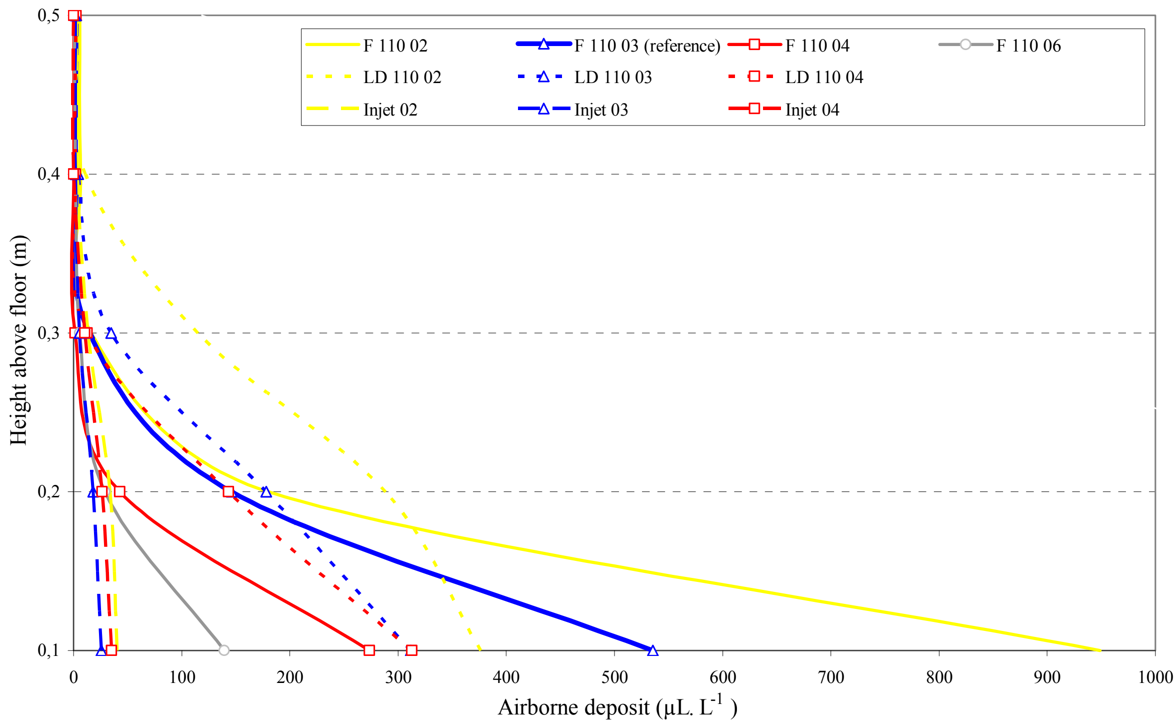

Figure 4.8: Average airborne wind tunnel deposits for different Hardi ISO nozzle sizes and types at a spray pressure of 3.0 bar and a wind speed of 2 m.s^{-1}

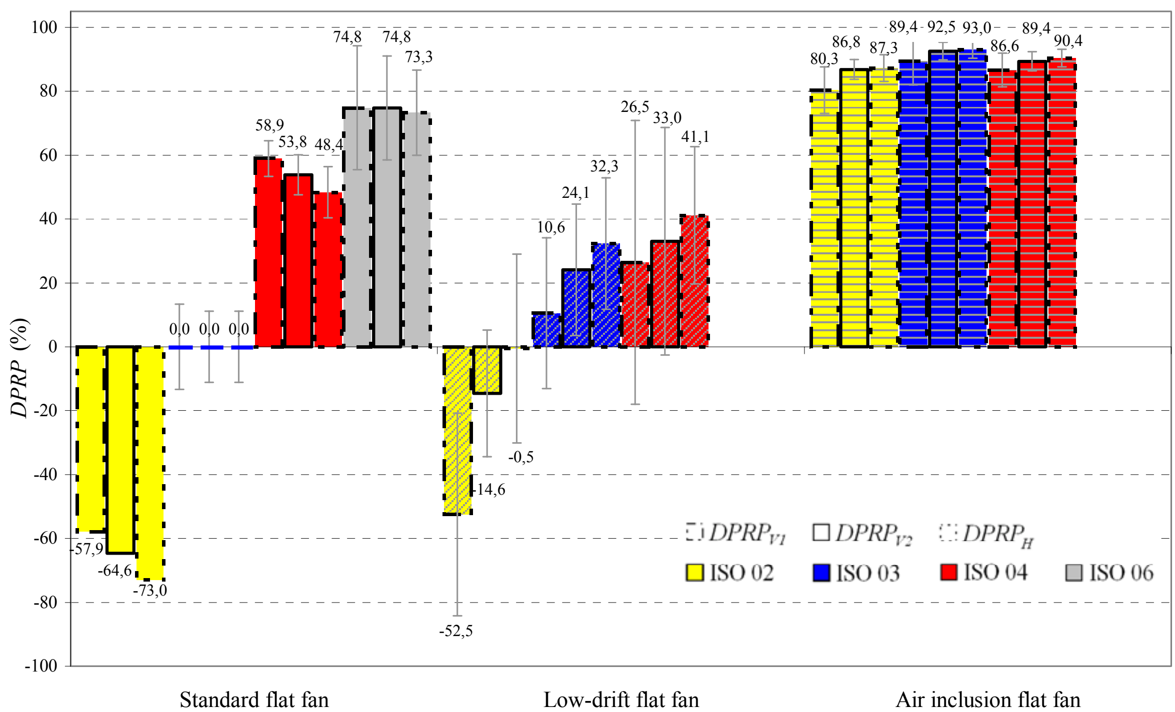

Figure 4.9: *DPRP$_{V1}$*, *DPRP$_{V2}$* and *DPRP$_H$* values and their 95% confidence intervals for different Hardi ISO nozzle sizes (and types) compared to the reference (Hardi ISO F 110 03 standard flat fan) at a pressure of 3.0 bar

For the standard flat fan nozzles at a spray pressure of 3.0 bar, $DPRP_{V1}$ values of -57.9, 0.0, 58.9 and 74.8% were found for ISO 02, 03, 04 and 06 nozzle sizes. Comparable results were found for $DPRP_{V2}$ and $DPRP_H$ values (Figure 4.9). In general, differences in

DPRP values were statistically significant (α = 0.05) for ISO 03, 04 and 06 standard flat fan nozzle sizes. Only for $DPRP_{V2}$, the difference between ISO 04 and ISO 06 could not be demonstrated statistically at a level of significance of 0.05. This demonstrates the important effect of nozzle size on drift potential for this nozzle type. This effect can mainly be attributed to differences in droplet characteristics (Chapter 3) and is discussed in detail in Chapter 6. Miller *et al*. (1995 b) and Ghosh and Hunt (1998) also mentioned that larger nozzle sizes have higher entrained air velocities, a more dense spray and therefore provide a greater resistance to the airflow. For the ISO 02 standard flat fan nozzles, no statistical analysis was performed because no repetitions were carried out.

Similarly, for the low-drift nozzles, *DPRP* values increase with increasing nozzle sizes but because of the relative high standard deviations and the rather limited number of measurements, this obvious effect of nozzle size cannot be demonstrated statistically at a level of significance of 0.05. For the low-drift nozzles, it is important to consider that there is a clear variation in *DPRP* values for the three different approaches to calculate drift potentials. $DPRP_{V1}$ values are always the lowest followed by $DPRP_{V2}$ and $DPRP_{H}$ values for one and the same nozzle-pressure combination. For example, for the ISO 02 low-drift nozzles, $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_{H}$ were, respectively, -52.5, -14.6 and -0.5%. These are totally different results depending on the measuring protocol and the data analysis. This issue is discussed in more detail below.

For the air inclusion nozzles, the effect of nozzle size on *DPRP* values is less clear and in general statistically not significant (α = 0.05). Only in the case of $DPRP_{V2}$ a significant difference was found between the ISO 02 ($DPRP_{V2}$ = 86.8%) and ISO 03 air inclusion nozzles ($DPRP_{V2}$ = 92.5%). *DPRP* values are in each case very high (80.3 up to 93.0%) going together with low fallout and airborne spray deposits (Figure 4.7 & Figure 4.8) and the highest *DPRP* values were found for the ISO 03 air inclusion nozzles. Taylor *et al*. (1999) also found reductions in fallout deposits using air inclusion nozzles, varying from 86 up to 91% depending on the nozzle size. They also found the lowest deposits for the ISO 03 air inclusion nozzles.

In conclusion, nozzle type as well as nozzle size generally have an important effect on *DPRP* values. The bigger the ISO nozzle size, the higher *DPRP* values for the standard and low-drift flat fan nozzles at a constant spray pressure. Similarly, air inclusion nozzles generally have higher *DPRP* values followed by the low-drift and the standard flat fan nozzles for the same nozzle size and spray pressure. Only for the ISO LD 110 04 nozzles, lower *DPRP* values were found compared with the ISO F 110 04 nozzles. The combined effect of nozzle size and type on $DPRP_{V1}$ values is presented in Figure 4.10 and in Annex 9 for $DPRP_{V2}$ and $DPRP_{H}$.

Comparing results conducted by the three different approaches described in section 4.3.2 namely, $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_{H}$, some interesting conclusions can be drawn. Mainly because of the rather limited number of repetitions, none of the $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_{H}$ values were significantly different (α = 0.05) for one and the same nozzle-pressure combination. In spite of this, some clear tendencies can be observed. For the standard flat fan nozzles (mainly the ISO 02 and 04 nozzle sizes), $DPRP_{V1}$ values were the highest followed by $DPRP_{V2}$ and $DPRP_{H}$. This means that by comparing with the reference spraying, airborne deposits are relatively lower than fallout deposits. For example for the ISO F 110 02 nozzle, $DPRP_{H}$ was -73.0% and $DPRP_{V1}$ was -57.9%.

For the low-drift nozzles opposite results were found. $DPRP_H$ values were the highest followed by $DPRP_{V2}$ and $DPRP_{V1}$. Again, this means that relative to the results from the reference spraying, fallout deposits are lower than airborne deposits. For example for the ISO LD 110 02 nozzle, fallout deposits are almost equal to the fallout deposits of the reference spraying ($DPRP_H$ = -0.5%) while airborne deposits are significantly higher for the ISO LD 110 02 nozzles compared with the reference spraying ($DPRP_{V1}$ = -52.5%). Similar tendencies were found for the ISO LD 110 03 and LD 110 04 nozzles as presented in Figure 4.9. Hence, for example for the F 110 02 and the LD 110 02 nozzles, $DPRP_{V1}$ values are almost equal, respectively, -57.9% and -52.5% while $DPRP_H$ values are totally different, respectively, -73.0% and -0.5%.

For the air inclusion nozzles, a relatively good agreement between $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$ values was found and exposure time did not seem to have an important effect on spray deposits as mentioned before by Andersen *et al*. (2000). All of this is important in the interpretation of wind tunnel data for different nozzle types and sampling methodologies. In Chapter 6, results from the wind tunnel experiments are compared with results from field drift experiments and the different *DPRP* values are evaluated based on real drift data and related with droplet characteristics.

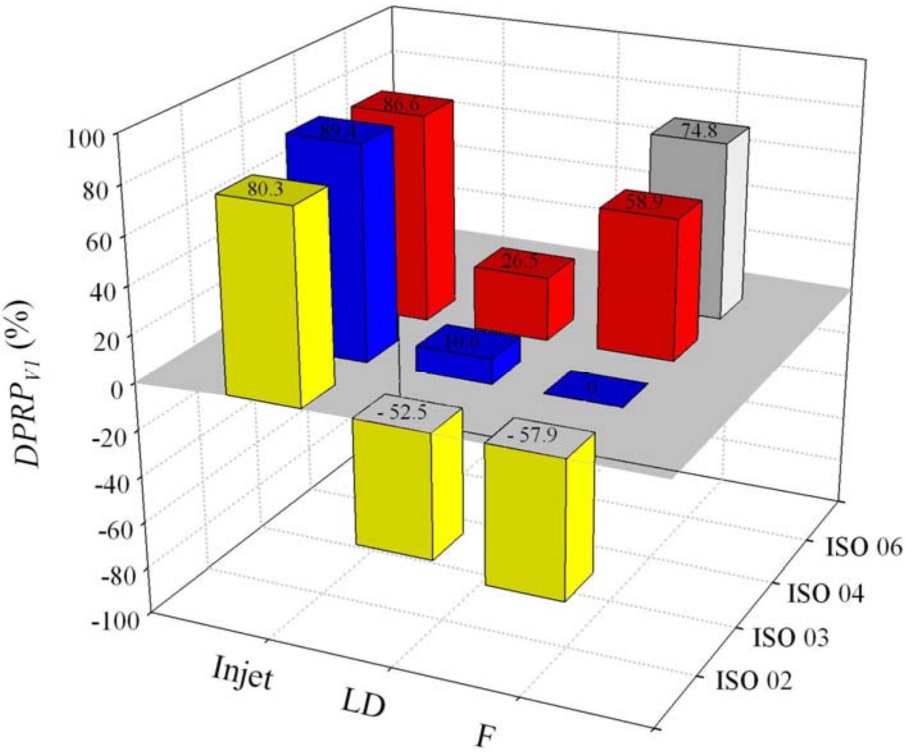

Figure 4.10: $DPRP_{V1}$ values for different ISO sizes (02, 03, 04 and 06) of Hardi standard flat fan (F), low-drift (LD) and air inclusion nozzles (Injet) at a spray pressure of 3.0 bar

4.3.5. Effect of spray pressure

A limited series of wind tunnel measurements were carried out with the Hardi ISO F 110 03 standard flat fan reference nozzle at a reduced spray pressure of 2.0 bar and at the reference spray pressure of 3.0 bar, to investigate the effect of spray pressure on drift potential. All measurements were done with a nozzle height of 0.50 m and a wind speed of 2 $m.s^{-1}$ as described in Table 4.1 (experiments *c 1*-3 and *rs 1-18*). Figure 4.11 presents the fallout spray profiles and Figure 4.12 the airborne spray profiles for spray pressures of 2.0 and 3.0 bar. Spray deposits are presented in detail in Table 4.2, Table 4.3 and Annex 7.

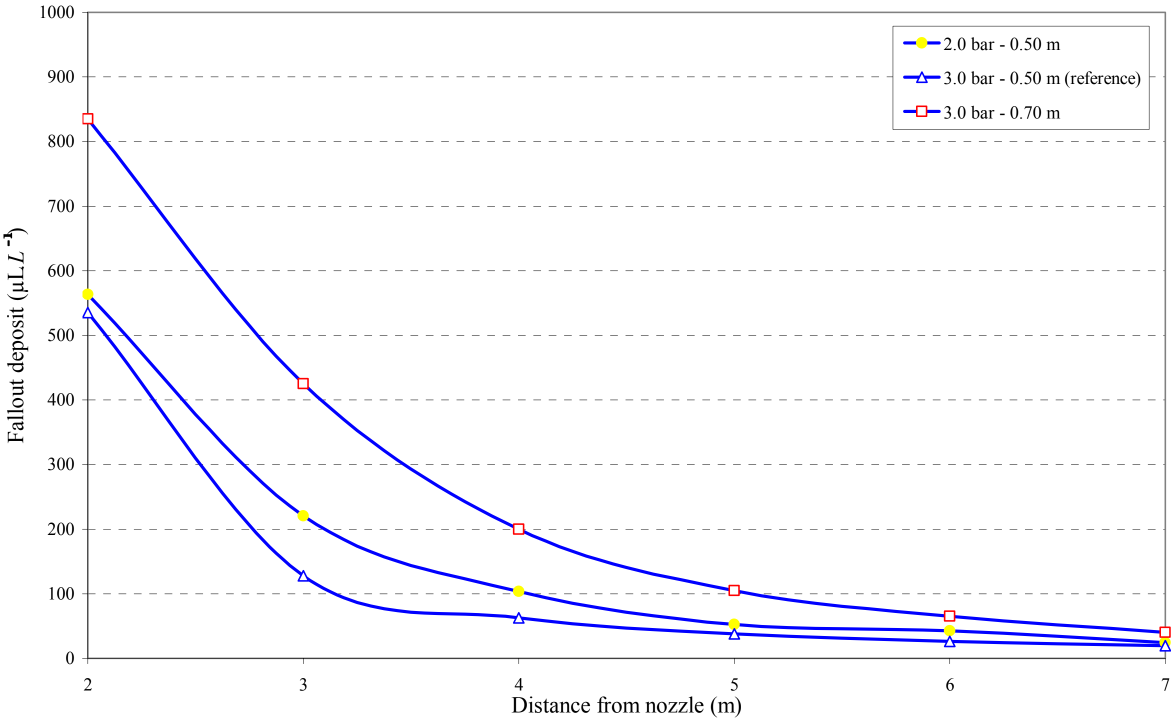

Figure 4.11: Average fallout wind tunnel deposits at a wind speed of 2 $m.s^{-1}$ for the Hardi ISO F 110 03 nozzle at 0.50 m nozzle height, at 2.0 and 3.0 bar (reference) and at 0.70 m nozzle height at 3.0 bar spray pressure

These results show that reducing spray pressure from 3.0 to 2.0 bar significantly (t-test; $\alpha = 0.05$) increases fallout as well as airborne downwind spray deposits with $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$ values of, respectively, -74.6, -48.4 and -34.1%. From the PDPA laser measurements (Chapter 3), we observed that reducing pressure from 3.0 to 2.0 bar for this nozzle type, has no significant effect on droplet sizes and reduces droplet velocities slightly. This is the main reason for the increase in spray deposits together with variation of the entrained air velocities which are higher for higher spray pressures. As described in section 4.2.4, values for deposits have been normalised to a common rate of liquid emission by the nozzle and that liquid flow rates are higher at higher spray pressures (Table 4.1).

Refering to other studies, Miller (1998) measured little difference in downwind deposits at pressures of 2.0, 3.0 and 4.0 bar for the smaller nozzle sizes. Taylor *et al*. (1999) found that changing the operating pressure influenced fallout and airborne deposits although the magnitude of this change was less than that due to changing the nozzle size and type, so that pressure changes are a less significant method of reducing drift.

Besides the effect on the amount of downwind deposits, changing pressure seemed to have an effect on the form of the airborne spray profile with generally higher deposits for the higher collector lines at the lower pressure as illustrated in Figure 4.12. This explains the difference between $DPRP_{V1}$ (= -74.6%), based on the first moment of the airborne spray profile, and $DPRP_{V2}$ (= -48.4%), based on the surface under the measured airborne deposit curve.

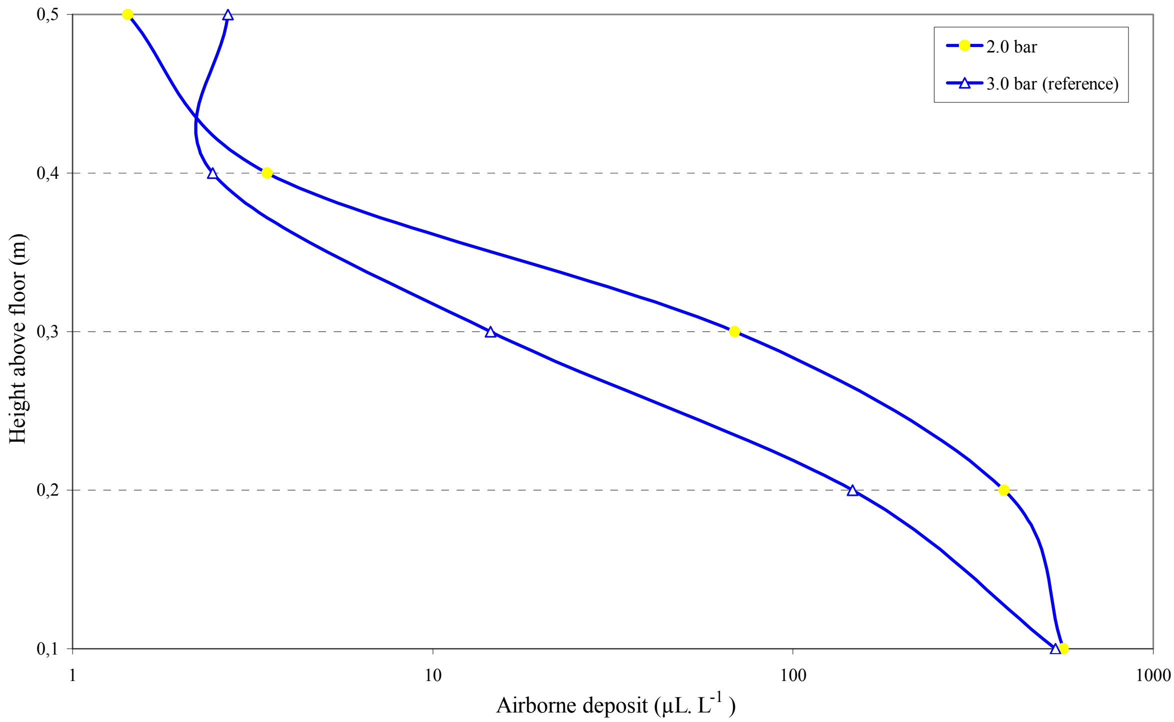

Figure 4.12: Airborne spray profiles for Hardi ISO F 110 03 standard flat fan nozzle at spray pressures of 2.0 and 3.0 bar (reference)

4.3.6. Effect of nozzle height

Figure 4.11 presents the fallout spray profiles for nozzle heights of 0.50 and 0.70 m for the Hardi ISO F 110 03 reference nozzle at 3.0 bar and a wind speed of 2.0 $m.s^{-1}$. These results are based on experiments *rs 1-18* and *e 1* (Table 4.1) and are presented in more detail in Table 4.2, Table 4.3 and annex 7. Airborne spray deposits were not brought into account because of the difference in height compared with the other measurements but it is very likely that the centre of the downwind airborne spray profile is raised to the greater release height (Taylor *et al*., 2004).

Although the number of experiments was very limited, it was observed that increasing nozzle height from 0.50 up to 0.70 m increases fallout volumes at the different collector distances. A total increase in fallout deposits of about 131% was found ($DPRP_H$ = -131%, Table 4.4). This means that increasing boom height from 0.50 to 0.70 m increases fallout spray deposits by a factor of about 2.3. Combellack *et al*. (1996) measured an increase of 72% when boom height was increased from 0.35 to 0.50 m. This important influence of boom height on downwind deposits is supported by field studies by among others de Jong *et al*. (2000) and Mueller and Womac (1997) as described in section 2.2.2.1.

4.3.7. Effect of wind speed

As described in Table 4.1, for the standard flat fan ISO 02 (experiment *b 1*) and ISO 03 (experiment *d 1*) nozzles, wind tunnel experiments were carried out at an increased wind speed of 5 m.s^{-1} with the standard spray pressure of 3.0 bar and nozzle height of 0.50 m. As mentioned before the air speed in the wind tunnel is used to reproduce spraying speeds and hence, air speeds of 5 m.s^{-1} are not typical of the conditions on most boom sprayers even not in combination with the natural wind.

The fallout and airborne deposit results of these experiments are shown in Figure 4.13 and Figure 4.14 together with the results of the corresponding experiments at the standard wind speed of 2 m.s^{-1} (experiments *a 1* and *rs 1-18*). As expected, the magnitude of fallout and airborne spray deposits, was much higher for the 5 m.s^{-1} than for 2 m.s^{-1} wind speed. Increasing wind speed also changed the form of the airborne spray profile in a way that the centre of gravity of the moving spray cloud is raised. This is confirmed by the results of Taylor *et al*. (2004). Consequently, the increase in fallout deposits is more important for distances further away from the nozzle (Figure 4.13). For example, for the F 110 03 nozzles, fallout deposits at a distance of 2 m increase with a factor of about 2.2 and at a distance of 5 m with a factor of about 10.1 when wind speed raises from 2 to 5 m.s^{-1}. Different other researchers like Western *et al*. (1989), Taylor *et al*. (1999), Smith and Miller (1994) also measured an increase in downwind deposits when wind speed increased.

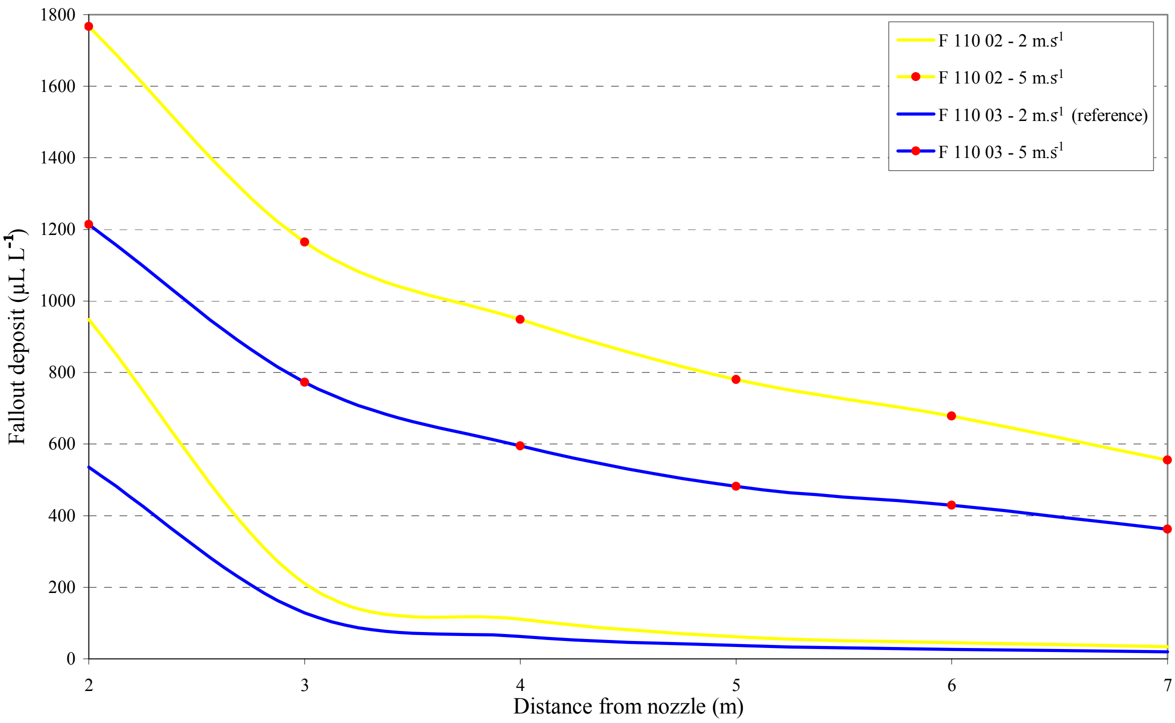

Figure 4.13: Average fallout wind tunnel deposits for the Hardi ISO F 110 02 and F 110 03 nozzles at a spray pressure of 3.0 bar, a nozzle height of 0.50 m and for wind speeds of 2 m.s^{-1} and 5 m.s^{-1}

Considering drift potentials for the reference nozzle F 110 03, DP_{V2} and DP_H values increased with factors of, respectively, 5.0 and 5.8 (Table 4.5). As mentioned before, DP_{V2} and DP_H represent the surfaces under the measured airborne and fallout deposit curves and hence, the effect of an increase in wind speed on DP_{V2} and DP_H is comparable. On the other hand, DP_{V1} increased with a factor of 9.7. This higher value for DP_{V1} can be explained by the fact that the effect of an increase in wind speed is more pronounced for the higher collectors and because DP_{V1} is based on the calculation of the first moment of the airborne spray profile. This is confirmed by the results of the F 110 02 standard nozzles where DP_{V1}, DP_{V2} and DP_H increased with factors of, respectively, 9.5, 4.5 and 5.1.

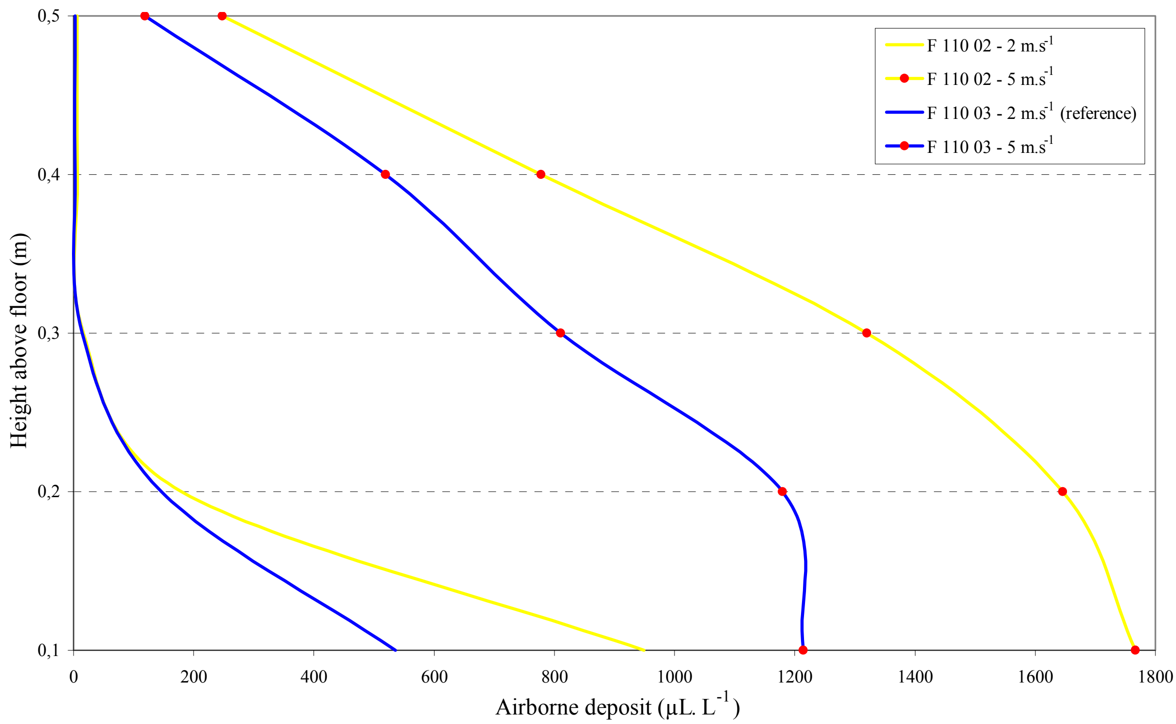

Figure 4.14: Average airborne wind tunnel deposits for the Hardi ISO F 110 02 and F 110 03 nozzles at a spray pressure of 3.0 bar, a nozzle height of 0.50 m and for wind speeds of 2 m.s^{-1} and 5 m.s^{-1}

Comparing fallout and airborne spray deposits between the F 110 02 nozzle and the F 110 03 reference nozzle, $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$ values of, respectively, -57.9, -54.6 and -73.0% were found for the measurements at a wind speed of 2 m.s^{-1} (Table 4.4). Based on the limited number of measurements at 5 m.s^{-1}, comparable values of -54.1, -48.1 and -54.3% for $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$ are calculated at a wind speed of 5 m.s^{-1} with the F 110 03 at 5 m.s^{-1} taken as the reference spraying. This is a good indication that *DPRP* values remain fairly constant irrespective of the wind speed conditions for the different approaches for these two nozzle-pressure combinations. The small difference in *DPRP* values of the F 110 02 between 2 and 5 m.s^{-1}, can possibly be attributed to the fact that wind speed does not proportionately raise downwind deposits namely, the increase in deposits is smaller for the finer sprays resulting in somewhat higher *DPRP* values for the F 110 02 at a wind speed of 5 m.s^{-1} (e.g. $DPRP_H$ = -54.3%) than at a wind speed of 2 m.s^{-1} (e.g. $DPRP_H$ = -73.0%). This effect is most pronounced for the fallout deposits and is confirmed by Nilars (2002). More experiments with different spray qualities with a wider range of wind speeds are necessary to confirm this finding. Note that Western *et al*. (1989) and Phillips and Miller (1999) showed a linear relationship between deposits and wind speed while Smith and Miller (1994) demonstrated a non-linear relationship.

Table 4.5: DP_{V1}, DP_{V2}, DP_H, $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$ values of the Hardi ISO F 110 02 and F 110 03 nozzles at a spray pressure of 3.0 bar, a nozzle height of 0.50 m and for wind speeds of 2 m.s^{-1} and 5 m.s^{-1}

	F 110 02			F110 03[a]		
	5 m.s^{-1}	2 m.s^{-1}	ratio	5 m.s^{-1}	2 m.s^{-1}	ratio
DP_{V1} (µL.m.L^{-1})	1336.6	141.3	9.5	867.4	89.5	9.7
DP_{V2} (µL.m.L^{-1})	570.3	125.4	4.5	385.0	76.2	5.0
DP_H (µL.m.L^{-1})	4731.7	920.6	5.1	3067.2	532.2	5.8
$DPRP_{V1}$ (%)	-54.1	-57.9		0	0	
$DPRP_{V2}$ (%)	-48.1	-54.6		0	0	
$DPRP_H$ (%)	-54.3	-73.0		0	0	

[a] Reference spray application; F, Hardi ISO 110 standard flat fan nozzles; *DP*, Drift potential; *DPRP*, Drift potential reduction percentage

4.4. Conclusions

Wind tunnel experiments can be used to measure airborne and fallout spray volumes under directly comparable and repeatable conditions. These experiments provide an efficient method of simulating a much wider range of conditions than would be available from field experiments alone and permit a drift potential to be calculated to assess relative drift risk. In this research, the Silsoe Research Institute (SRI) wind tunnel facility was used which is claimed to be the world's most advanced wind tunnel for research on the application of agricultural pesticides. With this set-up, single and static nozzles were exposed to a wind tunnel air speed.

In total, 51 wind tunnel experiments have been carried out corresponding with 510 deposit measurements including the reference spraying (*rs*) and 13 other spray applications (*os*). Different nozzle types (standard flat fan, low-drift flat fan and air inclusion), sizes (ISO 02, 03, 04 and 06), spray pressures (2.0 and 3.0 bar), nozzle heights (0.50 and 0.70 m) and wind speeds (2 and 5 m.s^{-1}) were evaluated. The reference spraying (*rs*) was defined as a Hardi ISO F 110 03 standard flat fan nozzle at 3.0 bar with a nozzle height of 0.50 m at a wind speed of 2 m.s^{-1} and was used for a comparative assessment of the different other spray applications.

Values for deposits were normalised and expressed as the volume of spray recovered from the lines for every litre of spray solution emitted by the nozzle. Based on these measurements, the drift potential (*DP*) of the different spray applications was calculated following three different approaches. The first approach was based on the calculation of the first moment of the airborne spray profile (DP_{V1}). In the second and third approach, the surface under the measured airborne (DP_{V2}) and fallout (DP_H) deposit curve was calculated. Drift potential values of the different spray applications were compared with the equivalent results obtained from the reference spraying by calculating their drift potential reduction percentage (*DPRP*) again using the three different approaches and resulting in $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$ values. These *DPRP* values express the percentage reduction of the drift potential compared with the reference spraying.

In general, the results showed the expected fallout profiles with the highest deposits closest to the nozzle and a systematic decrease with distance from the nozzle. Similarly, for the airborne deposit profiles, the highest deposits were found at the lowest collectors with an important systematic decrease with increasing heights.

For the same nozzle size and spray pressure, *DPRP* values are generally higher for the air inclusion nozzles followed by the low-drift nozzles and the standard flat fan nozzles and the effect of nozzle type is most important for smaller nozzle sizes. For example, for an ISO 02 nozzle size, $DPRP_{V2}$ values were -64.4% for the standard flat fan nozzles, -14.6% for the low-drift nozzles and 86.8% for the air injection nozzles. Only in the case of the ISO 04 standard and low-drift flat fan nozzles, this tendency was not followed with, for example, a $DPRP_{V2}$ value of 53.8% for the standard flat fan nozzle and 33.0% for the low-drift nozzle.

Besides nozzle type, the size of the nozzle is also related to the drift potential. The bigger the ISO nozzle size, the higher the *DPRP* values for the standard and the low-drift flat fan nozzles at a constant spray pressure. For example, for the standard flat fan nozzles at a spray pressure of 3.0 bar, $DPRP_{V1}$ values of -57.9, 0.0, 58.9 and 74.8% were found for ISO 02, 03, 04 and 06 nozzle sizes. In accordance with the effect of nozzle type, the effect of nozzle size can mainly be attributed to differences in droplet characteristics. Moreover, larger nozzle sizes have higher entrained air velocities, a more dense spray and therefore provide a greater resistance to the airflow. For the air inclusion nozzles, the effect of nozzle size on *DPRP* values is less clear and *DPRP* values were in each case very high (80.3 up to 93.0%).

Comparing results from the three different approaches namely, $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_{H}$, some interesting conclusions can be drawn. For the standard flat fan nozzles, $DPRP_{V1}$ values were the highest followed by $DPRP_{V2}$ and $DPRP_{H}$ while for the low-drift nozzles opposite results were found. For example for the F 110 02 and the LD 110 02 nozzles, $DPRP_{V1}$ values are almost equal, respectively, -57.9% and -52.5% while $DPRP_{H}$ values are totally different, respectively, -73.0% and -0.5%. This means that relative to the results from the reference spraying, fallout deposits are higher than airborne deposits for the standard flat fan nozzles whilst fallout deposits are relatively lower than airborne deposits for the low-drift nozzles. For the air inclusion nozzles, there was a relatively good agreement between $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_{H}$ values. All of this is important in the interpretation of wind tunnel data for different nozzle types and sampling methodologies.

Reducing spray pressure from 3.0 to 2.0 bar with the Hardi ISO F 110 03 reference nozzles, significantly increased fallout as well as airborne downwind spray deposits with $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_{H}$ values of, respectively, -74.6, -48.4 and -34.1%. This is mainly caused by the fact that reducing pressure from 3.0 to 2.0 bar for this nozzle type, has no significant effect on droplet sizes and reduces droplet velocities slightly (as found in Chapter 3) together with a decrease of entrained air velocities with lower spray pressures. Increasing nozzle height from 0.50 up to 0.70 m increased fallout deposits with about 131%.

Finally, increasing wind speed from 2 $m.s^{-1}$ to 5 $m.s^{-1}$ increased the magnitude of fallout and airborne spray deposits for the standard flat fan ISO 02 as well as for the ISO 03 nozzles. Moreover, the form of the airborne spray profile was changed in a way that the centre of gravity of the moving spray cloud is raised. Consequently, the increase in fallout deposits is more important for distances further away from the nozzle. For example, for the F 110 03 nozzles, fallout deposits at a distance of 2 m increase with a factor of about 2.2 and at a distance of 5 m with a factor of about 10.1 when wind speed is raised from 2 to 5 $m.s^{-1}$. For the F 110 03 nozzle, DP_{V2} and DP_H values increased with factors of, respectively, 5.0 and 5.8, while DP_{V1} increased with a factor of 9.7 again because the effect of an increase in wind speed is more pronounced for the higher collectors. *DPRP* values remain fairly constant irrespective of the wind speed conditions for the three different approaches for these two nozzle-pressure combinations. The small difference in *DPRP* values of the F 110 02 between 2 and 5 $m.s^{-1}$, can possibly be attributed to the fact that the increase in deposits is smaller for the finer sprays resulting in slightly higher *DPRP* values at a wind speed of 5 $m.s^{-1}$ (e.g. $DPRP_H$ = -54.3%) than at a wind speed of 2 $m.s^{-1}$ (e.g. $DPRP_H$ = -73.0%).

In Chapter 6, results from the wind tunnel experiments are compared with results from field drift experiments and the different *DPRP* values are related with droplet characteristics and evaluated based on real drift data from the field experiments.

Chapter 5 ***Drift experiments in field conditions***

5.1. Introduction

Spray drift and risks connected with application of pesticides in agriculture are attracting increased attention from the general public as well as the scientific community. Drift of pesticides caused by spraying has been recognised as a major problem for the environment.

Spray drift is affected by many factors (§ 2.2) like the weather conditions (Gilbert & Bell, 1988; Craig *et al*., 1998), the physical properties of the spray solution (Bode *et al*., 1976; Butler Ellis & Bradley, 2002; Klein & Johnson, 2002), the crop characteristics (Taylor *et al*., 1999; van de Zande *et al*., 2006) and the spray application itself. Different spray application factors like spray boom height (Teske & Thistle, 1999; de Jong *et al*., 2000), air assistance (van de Zande *et al*., 2000 a), shielded sprayer booms (Wolf *et al*., 1993; Cenkowski *et al*., 1994; Sidahmed *et al*., 2004), nozzle type and pressure (Heijne *et al*., 2002; Klein & Johnson, 2002) and driving speed (Miller & Smith, 1997; Ghosh & Hunt, 1998) have already been evaluated. A detailed description of the state of the art is presented in sections 2.2.1 and 2.2.2.

Although some field drift data for horizontal boom sprayers (Ganzelmeier & Rautmann, 2000; van de Zande *et al*., 2000 b; Hewitt & Wolf, 2004) and for aerial sprayings (Bird *et al*., 1996; Teske *et al*., 2002) have been published, there is still a need for accurate, detailed field drift measurements to enlarge the international drift database and to obtain absolute drift values. Moreover, additional information is necessary about the effect of the climatological conditions on the amount of spray drift to compare measurements with different spraying techniques to a reference spray under different weather conditions.

The objectives of this study were:

- To formulate and develop a reliable and feasible spray drift measuring protocol for horizontal boom sprayers according to the International Standard ISO 22866 (2005),
- To investigate the effect of meteorological conditions on the amount of near-field spray drift for the reference spraying and to investigate the relative importance of the different climatological factors,
- To develop a predictive relationship for drift deposits for a reference spraying for varying atmospheric conditions,
- To measure the amount of near-field spray drift for different spray application techniques and to compare these drift results with the reference spraying,
- To investigate the effect of nozzle type (standard flat fan, low-drift flat fan and air inclusion nozzles), nozzle size (ISO 02, 03, 04 and 06), spray pressure (2.0, 3.0 and 4.0 bar), boom height (0.30, 0.50 and 0.75 m), driving speed (4, 6, 8 and 10 km.h^{-1})

and air assistance on the amount of sedimenting spray drift,
- To obtain meteorological and drift data to validate a computational fluid dynamics drift-prediction model for field crop sprayers (Baetens *et al*., 2006; 2007 a).

Results of the field drift measurements were published in Nuyttens *et al.* (2005 b; 2006 c & d; 2007 a & d).

5.2. Materials and methods

The comparison of drift data from drift studies conducted by different researchers is often very complex because different techniques, tracers, experimental designs and test conditions yield different results. Numerous researchers already carried out field drift measurements in one way or another like Bode *et al*. (1976), Göhlich (1983), Permin *et al*. (1992), Fox *et al*. (1993 a), Thacker *et al*. (1994), Bouse *et al*. (1994), Baldoin *et al*. (1998), de Snoo and de Wit (1998), Praat *et al*. (2000), Cross *et al*. (2001 a; b), Heijne *et al*. (2002), Klein and Johnson (2002), Weisser *et al*. (2002), Richardson *et al*. (2004), Bjugstad and Sønsteby (2006) and many others. To harmonize the different drift measurements, ISO Standard ISO 22866 (2005) 'Methods for field measurement of spray drift' has been developed. The measuring protocol developed and formulated in this study is in accordance with this standard which is described in section 2.3.4.1.

5.2.1. Spray liquid

Although tracer methods have been shown to have a number of practical limitations, most of these can be circumvented by a thoughtful selection of tracers and attention to experimental procedures and analytical techniques.

For the assessment of drift in this study, a fluorescent tracer namely brilliant sulfoflavine (BSF) was used at a concentration of 3 $g.L^{-1}$. This tracer is highly water-soluble, has a low toxicity and has already been used successfully in many other deposit measurements as described in section 2.3.1.3 (Bau *et al*., 1971; Bode *et al*., 1976; Smith *et al*., 1982 b; Sanderson *et al*., 1993; Cai & Stark, 1997; van de Zande *et al*., 2000 b; de Jong *et al*., 2000; Smith *et al*., 2000 a; Heijne *et al*., 2002). Moreover, it offers high sensitivity with a very low detection limit (0.0005-0.005 $\mu g.cm^{-2}$). The analysis is relatively easy and inexpensive, and exposure of both the environment and bystanders to pesticides is avoided (Fox *et al*, 1990; 1993 a). This tracer was selected after a series of recovery, stability and wind tunnel experiments with other possible tracers like metal ions, a salt and a fungicide (Brusselman *et al*., 2005) as prescribed by the International Standard ISO 22866 (2005). A photostability test was carried out to investigate the sensitivity of BSF to photodegradation. A decrease of 7.2% of the initial concentration was measured after a period of 5 minutes for an amount of spray liquid of 10 ml with a BSF concentration of 3 $g.L^{-1}$ subjected to an average sunlight intensity of 35 $W.m^{-2}$. The decrease of the original concentration was about the same after periods of 10, 15 and 20 minutes with an average sunlight intensity of 46.0 ± 16.8 $W.m^{-2}$ over the full experiment. These experimental results indicated that it is important to take into account the photodegradation and recovery of BSF in the field experiments although photodegradation is rather limited compared with other fluorescent tracers like eosine, fluorescein, tinopal, etc. (Cai & Stark, 1997).

With the addition of a water-soluble surfactant, i.e. Tween 20 at a volumetric concentration of 0.1%, the spray liquid has properties representative of liquids typically used in the application of plant protection products i.e. a surface tension of 47.9 ± 0.6 mN.m^{-1}, a liquid density of 1.01 ± 0.02 kg.L^{-1} and a relative extensional viscosity of 1.01 ± 0.01. This might be important because of possible effects of these characteristics on spray formation and drift as described in detail in section 2.2.3. Droplet size spectra measurements with and without the fluorescent dyes showed that fluorescent dyes do not significantly affect the droplet spectra (Hewitt *et al*., 1994).

5.2.2. Spray drift collectors

Measures of drift relate to either the deposition onto horizontal surfaces outside the treated area or to airborne spray profiles that can be characterised at given downwind distances from the treatment area. Deposition onto horizontal surfaces is relevant for the assessment of the risk of contamination of surface waters, adjoining crops and other susceptible off-target areas. The measurement of airborne profiles is relevant to the risk assessment relating to inhalation effects and to the direct contamination risk of vegetative structures at field boundaries (Miller *et al*., 1989 b; Taylor & Anderson, 1991). An overview of different drift-collecting and sampling techniques is presented in section 2.3.1.2.

Ground deposition was measured on horizontal collection surfaces placed at ground level with Machery-Nachel filter paper (type 751, 0.25 × 0.25 m², Filter Service N.V., Figure 5.3). This filter paper was selected after a series of experiments based on the retention and recovery characteristics (Brusselman *et al*., 2005). The recovery of BSF on filter paper using water is relatively high and constant provided that the liquid solution including the filter paper is intensively shaken for a period of about 20 minutes. This type of collectors has been used before by Norby and Skuterud (1975), Johnstone and Huntingdon (1977), Bui *et al*. (1998) and Mathers *et al*. (2000) and they were found to be a good and reliable method for collection of spray drift (Carlsen *et al*., 2006 a). They have a known collection surface, and hence, it is possible to estimate the absolute quantity of sedimenting spray deposit and to relate the captured drift to the output from the spraying system.

Before each treatment, the spray solution was thoroughly mixed and a tank sample of the spray solution was taken immediately before application to measure the actual fluorescent concentration. The potential tracer degradation and the recovery were estimated for each trial using three filter paper collectors loaded with a measured volume of the tracer solution with a known concentration originating from the tank sample as prescribed in the ISO 22866 standard (2005). These collectors are positioned at a safe distance upwind of the directly sprayed zone, to avoid cross-contamination by spraying and were exposed for the same period of time as the deposition samples. By measuring the amount of tracer recovered after the drift experiment, a factor accounting for photodegradation and recovery can be estimated - expressed as recovery (*R*c, %). This recovery factor is used for the calculation of the real drift values as described in section 5.2.3. An overview of the recoveries for the different experiments is presented in Annex 10. Average recovery was 79% (sd = 13%). Recoveries higher than 100% and lower than 52% were considered as outliers and replaced by, respectively, 100% and the average *Rc* of the corresponding measuring session.

After each drift experiment, the collectors were stored as quickly as possible (maximally 10 min.) into UV-light-tight jars filled with 0.70 litres of water to solubilize the tracer. This happened in a way that cross-contamination was minimized using gloves and collecting the farthest collectors first.

5.2.3. Determination of drift deposits

Drift samples were analysed by the Laboratory of Phytofarmacy (Department of Crop Protection, Faculty of Bioscience Engineering, Ghent University). Deposits of the spray tracer were extracted from the samples by extraction in 0.70 litres of water immediately after the drift experiment. The volume of the dilution liquid was minimized depending on the collection area and the volume of spray collected in order to maximize tracer recovery. When using a fluorescent dye as a tracer, it is important to optimize the excitation and emission wavelength of the fluorimeter to the tracer in order to maximize discrimination of the tracer from the background. Background signal can come from the collector, the dilution liquid and pollution of the capillary measuring cell in the fluorimeter. After 20 minutes of intensive shaking, the concentration of the tracer was measured in a Cary Eclipse fluorimeter at an excitation wavelength of about 442 nm and an emission wavelength of about 497 nm as determined in a preliminary experiment (Figure 5.1). The limit of detection for the set-up used in this research was about 0.0005 mg.L^{-1}.

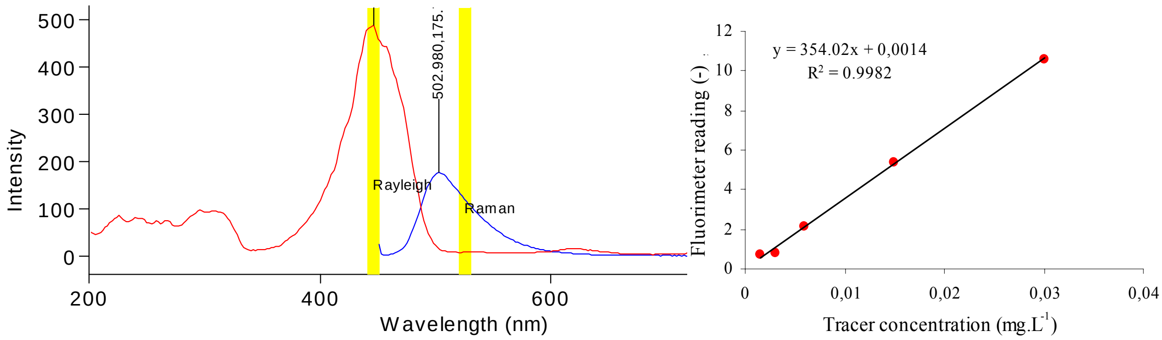

Figure 5.1: Excitation and emission spectra for a sample of brilliant sulfoflavine (red: excitation spectrum; blue: emission spectrum; yellow: disturbance light) and an example of a calibration curve

Fluorimeter measurements were carried out less than two hours after the experiment. The reading of the fluorimeter is related to the amount of tracer in solution through a calibration curve determined by sampling known concentrations of the tracer. Because of the wide range of tracer concentrations to be measured (from 0.0005 up to 7 mg.L^{-1}), three linear calibration curves were necessary for an accurate fluorimeter measurement corresponding with measuring ranges of respectively 0-0.01 mg.L^{-1}, 0.01-0.5 mg.L^{-1} and 0.5-7 mg.L^{-1} (Figure 5.1). These calibration curves were determined before each series of drift experiments. The corresponding calibration factors F_{cal} (mg.L^{-1}) determine the relationship between the fluorimeter reading (-) and the sample concentration of tracer (mg.L^{-1}):

$$C_{smpl} = (R_{smpl} - R_{blank}).F_{cal} \qquad (5.1)$$

with

C_{smpl} – Sample concentration of tracer (g.L^{-1}),
R_{smpl} – fluorimeter reading of the sample (-),
R_{blank} – fluorimeter reading of the blanks (collector + dilution water) (-),
F_{cal} – calibration factor (mg.L^{-1}).

From the sample concentration, the collector surface area, the recovery, the spray concentration and the volume of dilution liquid, the amount of spray deposit per unit area ($drift_{dep}$) can be calculated:

$$drift_{dep} = \frac{C_{smpl}.V_{dil}}{C_{spray}.A_{col}.\frac{Rc}{100}} \qquad (5.2)$$

with

$drift_{dep}$ – spray drift deposit (mL.cm^{-2}),
V_{dil} – Volume of dilution liquid (L),
Rc – Recovery (%),
C_{spray} – Spray concentration of tracer (g.L^{-1}),
A_{col} – Collection area of the spray drift collector (cm^2).

From this spray drift deposition figure, the percentage of spray drift on a collector can be calculated relating spray drift deposition to the amount applied in the field on the same unit of area. Hence, **drift deposition is calculated as a percentage of the deposition on the sprayed area** using the following formula:

$$drift_{\%} = \frac{drift_{dep} \times 10^7}{V_{app}} \qquad (5.3)$$

with

$drift_{\%}$ – spray drift percentage (%),
V_{app} – spray volume (L.ha^{-1}).

5.2.4. Spray application techniques

The spray applications were done with a Hardi Commander Twin Force trailed field sprayer with 27 m boom, a nozzle spacing of 0.50 m, Twin air assistance and a tank volume of 3200 litres. Based on common Belgian and international agricultural practice, the **reference spraying** (RS) was defined as follows:

- a standard horizontal spray boom without air assistance,
- a spray boom height of 0.50 m above the vegetative surface,
- a nozzle distance of 0.50 m,
- Hardi ISO F 110 03 standard flat fan nozzles at 3.0 bar (1.2 L.min^{-1}),
- a driving speed of 8 km.h^{-1}, resulting in an application rate of approximately 180 L.ha^{-1}.

In this study, the reference spraying was used to obtain a database with drift values for different weather conditions. In total, 32 reference drift experiments (768 drift measurements) were carried out. From these measurements, 27 experiments (RS 1-27) were used to investigate the effect of meteorological conditions on the amount of spray drift, the other five reference sprayings (RS_v 1-5) were used to validate the findings.

Besides the reference sprayings (RS & RS_v), 76 other sprayings (OS) were performed for 20 different combinations (identified as A up to T) of nozzle type (standard flat fan, low-drift, air inclusion) and size (ISO 02, 03, 04 and 06), spray pressure (2.0, 3.0 and 4.0 bar), driving speed (4, 6, 8 and 10 km.h^{-1}), spray boom height (0.3, 0.5 and 0.75 m) and the use of air assistance. Details about the spraying equipment settings for these other sprayings are given in Table 5.1. The average forward speed of the sprayer during each experiment was calculated by measuring the time to travel the spray distance of 100 m.

Because the conditions during a field measurement of spray drift are influenced by variables relating to the weather, crop conditions and spray boom movements that cannot be fully controlled, it is not possible to replicate a given measurement. Therefore, each experiment was carried out at least three times and at each measuring day, reference sprayings as well as other sprayings were combined. In total 108 different sprayings (2592 drift measurements) were carried out.

Figure 5.2: Hardi Commander Twin Force trailed field sprayer with 27 m boom, Twin air assistance and a tank volume of 3200 litres

Table 5.1: Spraying equipment settings for the different treatments

Experi-ment	Nozzle Type	ISO nozzle size	Pressure (bar)	Speed (km.h^{-1})	Flow rate (L.min^{-1})	Application rate (L.ha^{-1})	Boom height (m)	Air assist-ance	Number of repetitions
				VARIABLE: NOZZLE TYPE (ISO 02)					
A 1-3	F	02	3.0	8	0.8	120	0.5	no	3
B 1-3	LD	02	3.0	8	0.8	120	0.5	no	3
C 1-3	Injet	02	3.0	8	0.8	120	0.5	no	3
				VARIABLE: NOZZLE TYPE (ISO 03)					
RS	F	03	3.0	8	1.2	180	0.5	no	27
D 1-3	LD	03	3.0	8	1.2	180	0.5	no	3
E 1-3	Injet	03	3.0	8	1.2	180	0.5	no	3
				VARIABLE: NOZZLE TYPE (ISO 04)					
F 1-4	F	04	3.0	8	1.6	240	0.5	no	4
G 1-3	LD	04	3.0	8	1.6	240	0.5	no	3
H 1-4	Injet	04	3.0	8	1.6	240	0.5	no	4
				VARIABLE: NOZZLE SIZE					
A 1-3	F	02	3.0	8	0.8	120	0.5	no	
RS	F	03	3.0	8	1.2	180	0.5	no	
F 1-4	F	04	3.0	8	1.6	240	0.5	no	
I 1-3	F	06	3.0	8	2.4	360	0.5	no	3
				VARIABLE: SPRAY PRESSURE					
J 1-3	F	03	2.0	8	0.98	147	0.5	no	3
RS	F	03	3.0	8	1.2	180	0.5	no	
K 1-6	F	03	4.0	8	1.39	208.5	0.5	no	6
				VARIABLE: DRIVING SPEED					
L 1-6	F	03	3.0	4	1.2	360	0.5	no	6
M 1-5	F	03	3.0	6	1.2	240	0.5	no	5
RS	F	03	3.0	8	1.2	180	0.5	no	
N 1-4	F	03	3.0	10	1.2	144	0.5	no	4
				VARIABLE: SPRAY BOOM HEIGHT					
O 1-3	F	03	3.0	8	1.2	180	0.3	no	3
RS	F	03	3.0	8	1.2	180	0.5	no	
P 1-4	F	03	3.0	8	1.2	180	0.75	no	4
				VARIABLE: AIR ASSISTANCE					
Q 1-5	F	02	3.0	8	120	120	0.5	yes	5
R 1-3	F	03	3.0	8	180	180	0.5	yes	3
S 1-5	LD	02	3.0	8	120	120	0.5	yes	5
T 1-3	LD	03	3.0	8	180	180	0.5	yes	3
						Reference sprayings (RS 1-27 + RS$_v$ 1-5)			32
							Other sprayings (OS)		76
								Total	108

F, Hardi ISO 110 standard flat fan nozzles; LD, Hardi ISO 110 low-drift nozzles; Injet, Hardi ISO Injet air inclusion nozzles; RS, reference spraying; RS$_v$, reference spraying used for validation

5.2.5. Experimental design

Experiments were conducted in a flat mowed meadow. The average crop height was 0.10 m, this is important because crop characteristics have an important effect on drift values as demonstrated by Taylor *et al*. (1999) and van de Zande *et al*. (2006) and discussed in section 2.2.6. The trial site was in an open area without any obstructions to influence the airflow in the region of the measurement. Three spray lines and six measuring zones were marked in the field. An overview of the experimental set-up for the field measurements is given in Figure 5.3. The choice of the spray line and measurement zone was dependent on the wind direction in a way that the driving direction was as good as perpendicular to the wind direction at application time. The directly sprayed zone is defined as the spray boom length plus half the average nozzle spacing at each end of the boom as illustrated in Figure 2.18. Hence, an area with a length of 100 m and a width of 27 m was directly sprayed in a single pass.

Spray drift was determined by sampling in a defined downwind area. This research focused on near-field drift with drift measurement up to 20 metres from the directly sprayed zone. Three sampling lines (line A, B and C) of horizontal drift collectors were positioned in the centre of the spray swath with a distance of 10 m between them. For each sampling line, horizontal drift collectors were placed at 0.5, 1, 2, 3, 5, 10, 15 and 20 metres downwind of the sprayed area. These collectors were positioned to correspond to the top of the canopy (0.10 m) so as to remove filtration issues. In total, 24 horizontal drift collectors, corresponding with a total horizontal sampling area of 1.5 m², were used for each drift trial.

A co-ordinate reference system is used to describe the layout of the spray drift trial and the location of the spray drift collectors with:

- X dimension is the other horizontal axis 90° to X (normally wind direction),
- Y dimension is the axis in the direction of sprayer travel,
- Z dimension is the vertical axis (90° to X and Y).

The origin of the co-ordinate system is placed at the mid-point of the directly sprayed area as presented in Figure 5.3.

Since drift is expressed as a proportion of the application rate, it is important that some direct assessment of target deposits is made as part of the drift measurement procedure. This is obtained by placing three filter paper collectors randomly in the directly sprayed zone. These collectors were used to verify the theoretically applied spray volume in the field. Figure 5.4 shows some pictures of the experimental set-up.

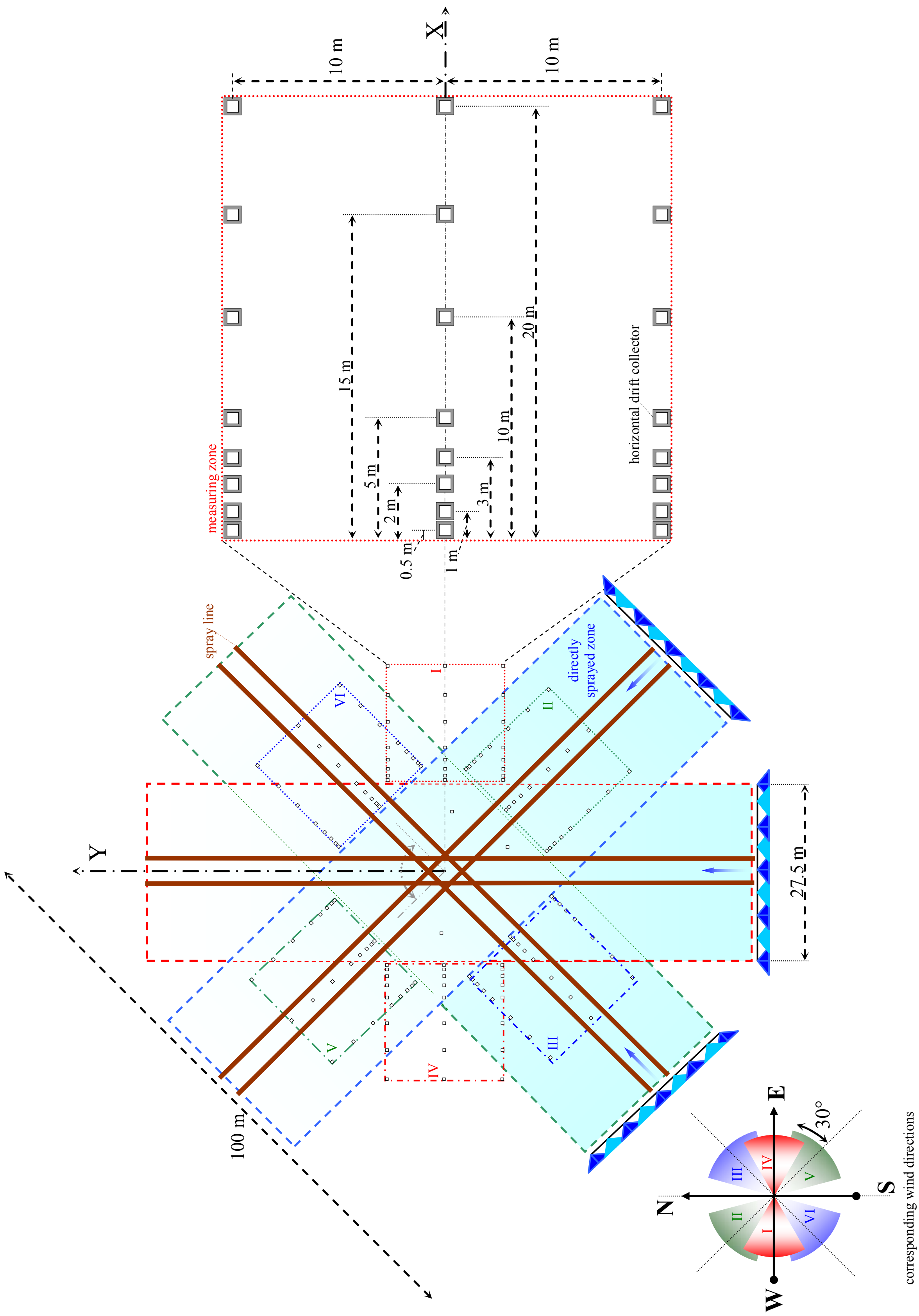

Figure 5.3: Schematic overview of the experimental set-up for the field drift measurements

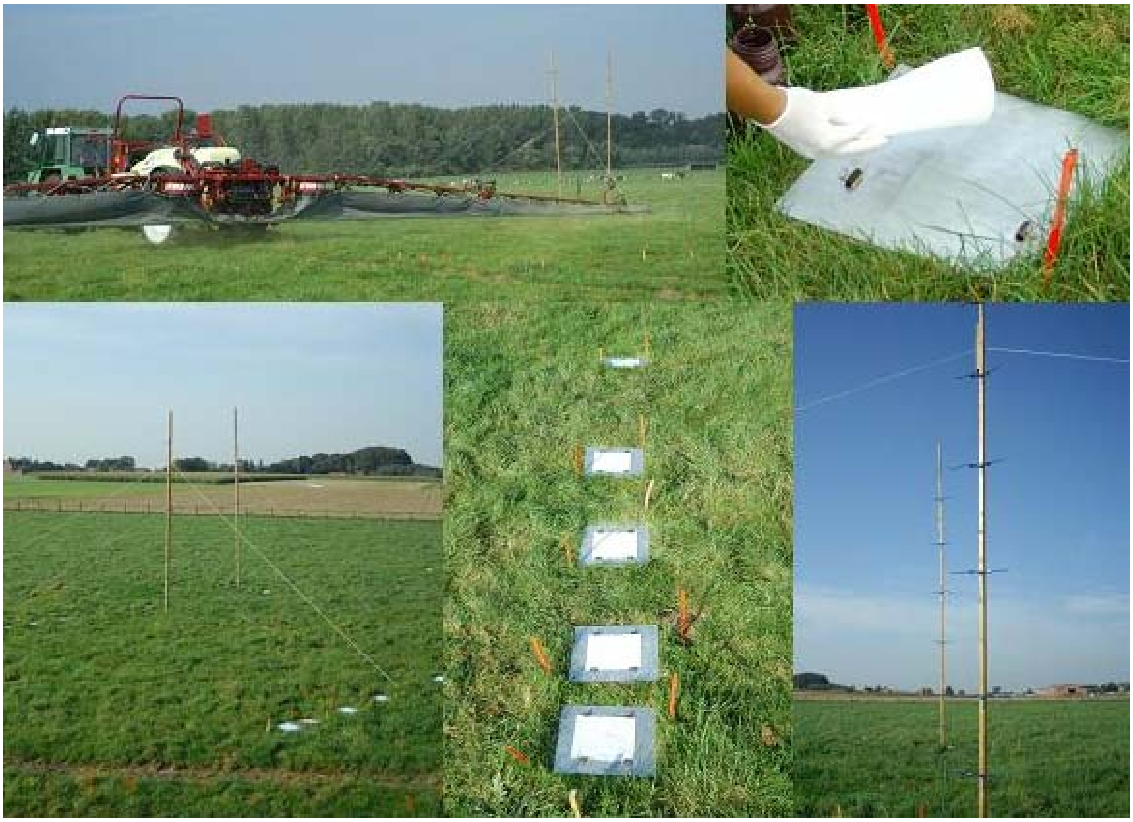

Figure 5.4: Some pictures of the experimental setup of the field drift measurements

5.2.6. Meteorological measurements

Meteorological parameters are monitored at a sampling rate of 0.33 Hz upwind of the sprayed area. In this way, measurements are not disturbed by the movement of the sprayer or the spray application. A Campbell Scientific weather station (Figure 5.5) with different sensors at an upwind distance of approximately 20 m from the track is used to determine the average wind speed during the spray experiment of about 45 s (V), the instantaneous wind speed (v, accuracy ± 2%) and wind direction (*dir*, accuracy ± 3°) at the moment of sprayer passage, measured at heights of 1.50 m ($V_{1.50m}$, $v_{1.50m}$ & $dir_{1.50m}$) and 3.25 m ($V_{3.25m}$, $v_{3.25m}$ & $dir_{3.25m}$) Temperature (accuracy ± 0.2°C) and relative humidity (accuracy ± 2%) at heights of 1.25 m ($T_{1.25m}$ & $RH_{1.25m}$) and 2.15 m ($T_{2.15m}$ & $RH_{2.15m}$) were also measured. An overview of the different meteorological parameters is presented in Table 5.2. For these measurements, the weather station is equipped with a CR 1000 Micrologger® (Campbell Scientific, Inc.) measurement and control module, two WindSonic1 ultrasonic anemometers (Gill Instruments, Inc.) and two Rotronic MP100A temperature and relative humidity probes (Rotronic AG).

When the measurement height is not mentioned in an index, the average of the two heights is used (T, V, RH, v and *dir*). The mean wind direction is preferably at 90° to the spray track during the period of spraying. An average maximum deviation of the ideal driving direction δ (°) of 40° to wind direction was allowed in these trials while the ISO 22 866 (2005) prescribes an average maximum deviation of 30° (§ 2.3.4.1). This was possible because the deviation of the ideal driving direction was brought into account during the analysis of the drift results as described in section 5.3.1.2. Based on the different measurements several other meteorological parameters are calculated:

- X_{H_2O} – absolute humidity of the air expressed in grams of water vapour per unit mass (kg) of dry air, given by:

$$X_{H_2O} = 622.\frac{(\frac{RH}{100}).p_w^s}{p_0 - (\frac{RH}{100}).p_w^s} \quad (5.4)$$

  where RH is the relative humidity in %, p_0 is the normal atmospheric pressure which is 101 325 Pa and p_w^s is the saturation water vapour pressure in Pa at a given temperature T in °C and calculated by (Buck, 1981):

$$p_w^s = 611.21.e^{(\frac{17.502.T}{240.97+T})} \quad (5.5)$$

- $A.S.$ – atmospheric stability in °C.m^{-1}, a term used to describe the vertical movement of air in the atmosphere which is associated with the temperature gradient in the planetary boundary layer, defined as:

$$A.S. = \frac{dT}{dz} = \frac{T_{2.15m} - T_{1.25m}}{0.9} \quad (5.6)$$

- $T.I.$ – turbulence intensity, calculated as follows:

$$T.I. = \frac{v_{max} - v_{min}}{V} \quad (5.7)$$

  where v_{max}, v_{min}, and V are the maximum, the minimum and the average wind speed during the drift experiment,
- T_d – dew-point temperature in °C, defined as:

$$T_d = \frac{237.7 \times \log(\frac{10^{\frac{7.5.T}{237.7+T}}.RH}{100})}{7.5 - \log(\frac{10^{\frac{7.5.T}{237.7+T}}.RH}{100})} \quad (5.8)$$

  where T and RH are the average temperature and relative humidity during the drift experiment.

As described in ISO 22866 (2005, § 2.3.4.1), measurements are preferably made in atmospheric conditions with wind speeds of at least 1 m.s^{-1}, a mean wind direction of 90° ± 30° to the spray track during the period of spraying and temperatures of between 5°C and 35°C. The measuring protocol is in accordance with this standard except for the allowed average maximum deviation of the ideal driving direction, as mentioned above.

Table 5.2: Overview of the different meteorological parameters investigated during the field drift experiments

Parameter	Description	Units
A.S.	Atmospheric stability	°C.m^{-1}
dir	Wind direction based on measurements at heights of 1.50 and 3.25 m	°
$dir_{1.50}$	Wind direction at a height of 1.50 m	°
$dir_{3.25}$	Wind direction at a height of 3.25 m	°
δ	Deviation of the ideal driving direction on wind direction	°
RH	(average) relative humidity (during the spray experiment) based on measurements at heights of 1.25 and 2.15 m	%
$RH_{1.25m}$	Average relative humidity at a height of 1.25 m	%
$RH_{2.15m}$	Average relative humidity at a height of 2.15 m	%
T	(average) temperature (during the spray experiment) based on measurements at heights of 1.25 and 2.15 m	°C
T_d	Dew-point temperature	°C
T.I.	Turbulence intensity	-
$T_{1.25m}$	Temperature at a height of 1.25 m	°C
$T_{2.15m}$	Temperature at a height of 2.15 m	°C
V	Average wind speed during the spray experiment based on measurements at heights of 1.50 and 3.25 m	m.s^{-1}
$V_{1.50m}$	Average wind speed during the spray experiment at a height of 1.50 m	m.s^{-1}
$V_{3.25m}$	Average wind speed during the spray experiment at a height of 3.25 m	m.s^{-1}
v	Instantaneous wind speed at the moment of passing a sampling line based on measurements at heights of 1.50 and 3.25 m	m.s^{-1}
$v_{1.50m}$	Instantaneous wind speed at the moment of passing a sampling line at a height of 1.50 m	m.s^{-1}
$v_{3.25m}$	Instantaneous wind speed at the moment of passing a sampling line based at a height of 3.25 m	m.s^{-1}
X_{H_2O}	Absolute humidity of the air expressed in grams of water vapour per unit mass of dry air	g.kg^{-1}

Figure 5.5: Campbell Scientific weather station

5.3. Results and discussion

5.3.1. Reference spraying and the effect of meteorological conditions

5.3.1.1. Atmospheric conditions

Table 5.3 shows the most important meteorological variables for the 27 drift trials with the reference spraying (RS) used to investigate the effect of meteorological conditions. The spreading of the average temperature (*T*), absolute humidity (X_{H_2O}) and wind speed (*V*) is presented in Figure 5.6 by means of boxplots. The reference spraying is defined as a standard horizontal spray boom without air assistance, a spray boom height of 0.50 m, a nozzle distance of 0.50 m, ISO 110 03 standard flat fan nozzles at 3 bar (1.2 $L.min^{-1}$) and a driving speed of 8 $km.h^{-1}$, resulting in an application rate of approximately 180 $L.ha^{-1}$. In seven cases, the deviation of the ideal driving direction exceeded 40°. For four other experiments, there were problems with the spray boom height and a pressure fall during the experiment (Table 5.3). These data were not used in the further analysis. This results in 19 useful drift trials corresponding with 456 drift measurements. Average temperature during the sprayings varied from 8.9 to 30.7°C, absolute humidity from 3.6 to 12.9 $g.kg^{-1}$, average relative humidity from 38.3 to 95.8% and average wind speed from 1.00 $m\ s^{-1}$ to 5.72 $m\ s^{-1}$. Hence, a wide range of climatological conditions was investigated.

Measurements were carried out at the end of August - beginning of September 2004, May 2005 and the end of March - beginning of April 2006. There were a total of 21 measuring days. Measurements were carried out during the entire day. In most cases, 24 treatments out of 27, measurements were carried out under unstable conditions illustrated by a negative sign in front of the *A.S.* value. From this point, a temperature of 16°C in combination with an absolute humidity of 8 $g.kg^{-1}$ and a wind speed of 3 $m.s^{-1}$ are defined as standard meteorological conditions. This combination of temperature and absolute humidity corresponds with a relative humidity of about 71%.

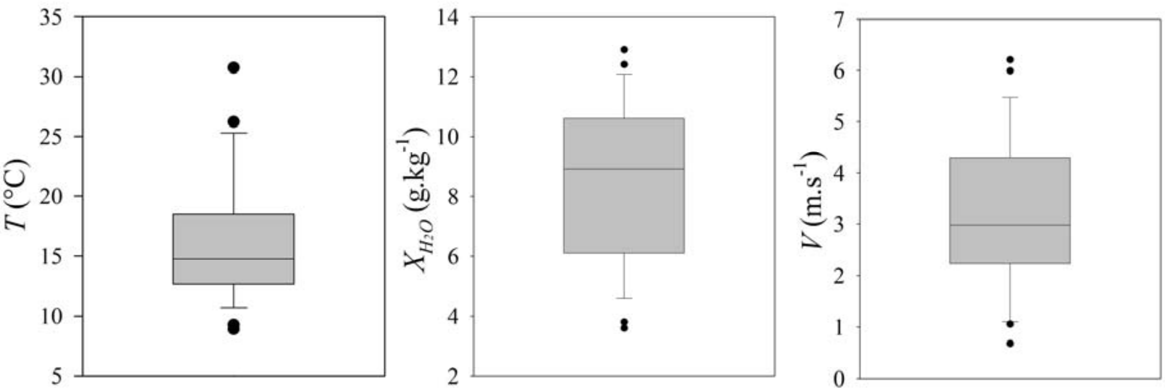

Figure 5.6: Range of average temperature (*T*), absolute humidity (X_{H_2O}) and wind velocity (*V*) measured during the 27 reference sprayings by means of boxplots indicating the 10th, 25th, 50th, 75th and 90th percentile of the measuring data

Table 5.3: Most important meteorological variables for the different reference experiments (RS)

Experiment	*RH* (%)	X_{H_2O} (g.kg^{-1})	*T* (°C)	$V_{1.50m}$ (m.s^{-1})	$V_{3.25m}$ (m.s^{-1})	*V* (m.s^{-1})	*δ* (°)	*A.S.* (°C.m^{-1})	*T.I*	T_d (°C)
RS 1[b]	63.7	11.7	23.7	2.38	3.47	2.93	56.9[a]	-0.37	0.51	15.4
RS 2[b]	65.0	12.0	23.8	4.89	6.00	5.44	49.9[a]	-0.25	0.65	15.8
RS 3	65.3	12.9	25.0	4.10	5.21	4.66	44.0[a]	-0.48	0.57	16.8
RS 4	42.0	11.6	30.7	2.08	2.73	2.41	23.8	-0.82	0.76	15.3
RS 5	79.5	10.6	18.5	3.60	2.92	3.26	13.3	0.31	0.56	14.0
RS 6	80.0	10.6	18.4	3.20	2.57	2.89	15.4	0.27	0.39	14.0
RS 7	74.7	6.3	11.5	0.58	0.68	0.63	36.1	-0.24	0.80	6.9
RS 8[b]	71.9	5.9	11.1	1.51	1.72	1.62	48.3[a]	-0.38	0.33	6.0
RS 9	74.8	6.3	11.5	2.46	2.98	2.72	40.0	-0.38	0.58	7.0
RS 10	64.9	5.9	12.7	1.82	2.24	2.03	99.5[a]	-0.37	0.60	6.1
RS 11	74.0	6.7	12.6	4.42	5.34	4.88	18.1	-0.41	0.79	7.8
RS 12	70.0	6.3	12.6	3.73	4.52	4.12	14.8	-0.33	0.75	7.1
RS 13	68.1	6.6	13.6	3.94	4.62	4.28	1.3	-0.41	0.71	7.6
RS 14	65.7	6.1	13.1	3.42	4.03	3.73	8.4	-0.32	0.69	6.6
RS 15	87.0	9.2	15.0	4.38	3.29	3.84	17.5	0.21	0.62	12.2
RS 16[c]	81.6	9.2	15.9	2.62	3.12	2.87	32.7	-0.37	0.63	12.1
RS 17	77.0	8.9	16.3	2.29	2.81	2.55	75.8[a]	-0.23	0.44	11.7
RS 18	93.1	6.6	8.9	0.94	1.06	1.00	16.5	-0.29	0.69	7.6
RS 19	87.6	9.1	14.7	1.09	1.11	1.10	16.3	-0.36	0.41	12.1
RS 20	84.0	9.3	15.6	1.29	1.36	1.33	49.3[a]	-0.41	0.47	12.3
RS 21	80.0	9.2	16.2	2.00	2.47	2.24	18.1	-0.47	0.48	12.1
RS 22	61.8	10.2	22.0	3.12	3.67	3.40	18.5	-0.44	0.65	13.6
RS 23	58.5	12.4	26.2	5.23	6.21	5.72	8.2	-0.48	0.77	16.3
RS 24	62.8	6.1	13.8	2.68	2.97	2.83	11.0	-0.41	0.29	6.6
RS 25	65.6	4.8	9.3	1.58	1.86	1.72	23.8	-0.44	0.82	3.1
RS 26	40.1	3.8	13.3	2.77	3.06	2.92	7.5	-0.45	0.79	0.0
RS 27	36.2	3.6	13.9	3.57	4.29	3.93	6.5	-0.54	0.50	-0.8
Average	**69.4**	**8.2**	**16.3**	**2.80**	**3.20**	**3.00**	**28.6**	**-0.33**	**0.60**	**9.8**

[a] Deviation of ideal driving direction > 40°; [b] Spray boom too high or too low during measurement; [c] Pressure fall during measurement; *RH*, average relative humidity; X_{H_2O}, Absolute humidity; *T*, average temperature; $V_{1.50m}$, average wind speed at 1.50 m; $V_{3.25m}$, average wind speed at 3.25 m; *V*, average wind speed; *δ*, deviation of ideal driving direction; *A.S.*, atmospheric stability; *T.I.*, turbulence intensity; T_d, dew-point temperature; RS, reference spraying

5.3.1.2. Sedimenting drift data

The sedimenting spray drift results from three arbitrarily chosen reference sprays (RS 14, 18 & 24) are plotted in Figure 5.7. Each drift value is the average of the results measured at the three sampling lines at a certain distance. The standard deviations are presented on the graph for the different collector distances by means of error bars. Note the logarithmic scale of the drift axis. The drift distances are calculated by dividing the distance of the horizontal collectors (0.5, 1, 2,…, 20 m) by the cosine of the deviation of the ideal driving direction δ and drift deposits are calculated as a percentage of the deposition on the sprayed area. Standard deviations of the other applications, not presented in this graph, are in the same range of magnitude. A complete overview of the measuring results of the different reference sprayings is presented in Annex 11 and Table 5.4. The considerable variation in drift values between the three sampling lines may be due to spray boom movements (van de Zande *et al*., 2006) and secondarily to small variations in wind speed, wind direction and spray line while passing the different sampling transects. Fox *et al.* (1993 a) and Salyani and Cromwell (1993) found similar variations in drift values.
More important is the fact that besides the variation between the three sampling lines for each reference spray, also a large variation between different reference sprays is found. This is illustrated by the very high standard deviations associated with the average drift values of the 19 successful reference sprays also presented in Figure 5.7. For example, drift deposits varied from 0.4% (RS 15) to 16.7% (RS 26) on the collector placed at 1 m of the directly sprayed zone. It is reasonable to assume that this variation is mostly caused by variations in weather conditions as suggested before by Bode *et al*. (1976). This hypothesis is investigated by carrying out a detailed regression analysis.

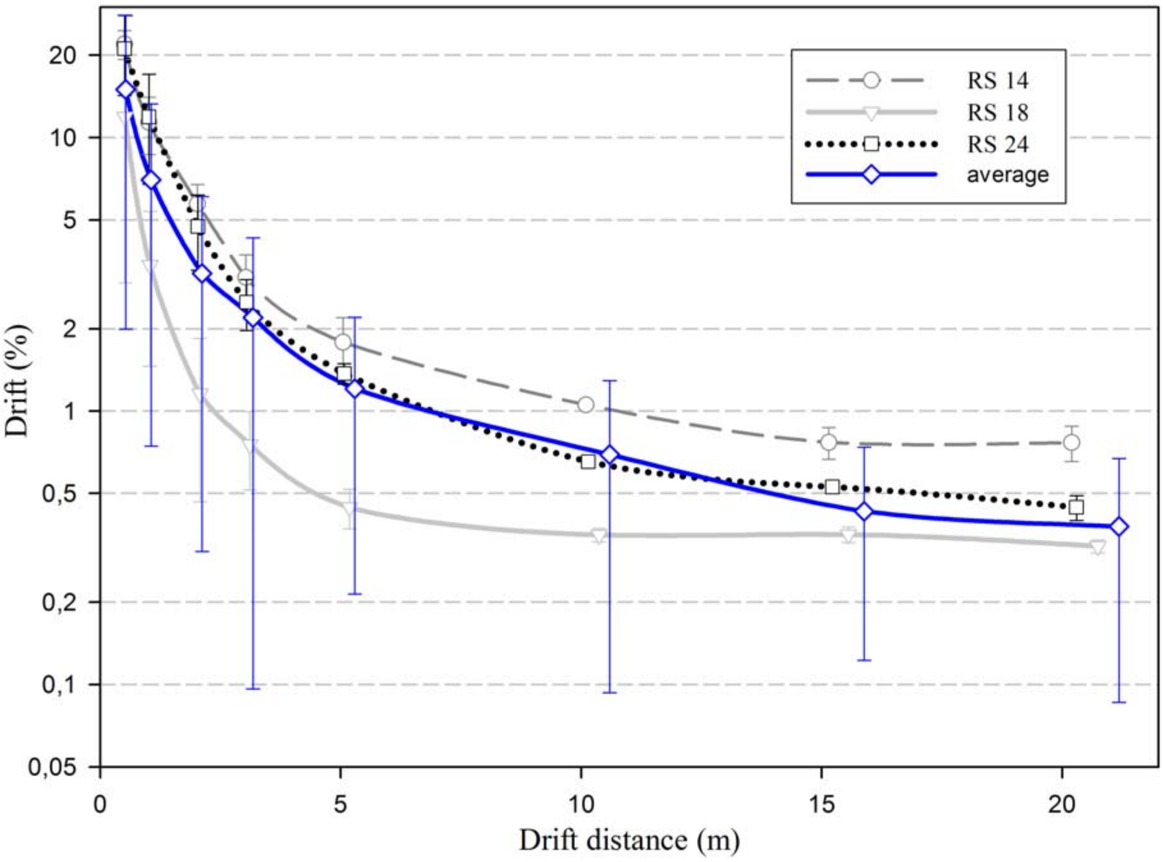

Figure 5.7: Average sedimenting drift data and standard deviations for three reference sprays (RS 14, 18 & 24) + the average drift curve based on 19 reference sprays

Table 5.4: Sedimenting drift data of the 19 reference sprayings (RS) and the average drift values (+sd)

	RS 4				RS 5				RS 6			
Collector distance (m)	Drift distance (m)	Drift (%) Line A	Line B	Line C	Drift distance (m)	Drift (%) Line A	Line B	Line C	Drift distance (m)	Drift (%) Line A	Line B	Line C
0.5	0.54	9.73	11.05	12.97	0.51	6.16	27.09	4.18	0.52	3.76	12.49	4.70
1	1.09	5.46	1.74	3.00	1.03	3.00	13.73	0.97	1.04	2.27	8.77	2.60
2	2.17	1.60	0.78	1.34	2.06	2.08	3.50	2.43	2.07	0.48	2.58	2.77
3	3.26	0.61	0.49	0.88	3.08	0.93	0.10	1.59	3.11	0.29	0.89	3.42
5	5.43	0.42	0.79	0.59	5.14	0.32	1.80	0.49	5.19	0.30	0.38	1.91
10	10.86	0.41	0.57	0.49	10.28	0.30	0.46	0.35	10.37	0.09	0.13	0.51
15	16.29	0.39	0.42	0.47	15.42	0.14	0.30	0.20	15.56	0.07	0.10	0.25
20	21.71	0.41	0.43	0.42	20.55	0.11	0.22	0.15	20.75	0.05	0.11	0.13

	RS 7				RS 9				RS 11			
Collector distance (m)	Drift distance (m)	Drift (%) Line A	Line B	Line C	Drift distance (m)	Drift (%) Line A	Line B	Line C	Drift distance (m)	Drift (%) Line A	Line B	Line C
0.5	0.60	11.91	11.75	11.16	0.66	10.70	27.09	22.48	0.52	4.06	15.60	6.62
1	1.20	6.64	5.21	4.18	1.32	7.10	17.30	12.45	1.04	2.54	7.92	4.10
2	2.39	2.24	1.98	1.68	2.64	5.61	12.29	5.72	2.08	2.18	5.01	3.14
3	3.59	1.55	1.04	1.10	3.95	3.63	8.59	4.16	3.12	1.31	2.58	1.96
5	5.98	0.71	0.50	0.47	6.59	2.31	3.03	2.47	5.19	0.78	1.43	1.53
10	11.96	0.48	0.39	0.38	13.18	0.88	1.33	1.44	10.39	0.67	0.52	0.92
15	17.95	0.36	0.36	0.36	19.76	0.73	0.79	0.88	15.58	0.45	0.75	0.59
20	23.93	0.37	0.35	0.36	26.35	0.65	0.77	0.61	20.77	0.39	0.43	0.57

	RS 12				RS 13				RS 14			
Collector distance (m)	Drift distance (m)	Drift (%) Line A	Line B	Line C	Drift distance (m)	Drift (%) Line A	Line B	Line C	Drift distance (m)	Drift (%) Line A	Line B	Line C
0.5	0.52	13.48	33.25	14.50	0.50	4.77	26.93	6.02	0.50	18.91	23.14	23.82
1	1.03	7.59	22.33	5.63	1.00	2.71	9.60	4.17	1.01	8.74	14.14	11.20
2	2.06	4.72	11.18	3.71	2.00	1.44	2.49	3.24	2.02	5.30	5.01	6.88
3	3.09	3.31	7.60	3.04	3.00	0.92	1.54	2.68	3.03	3.25	2.36	3.63
5	5.15	2.35	3.80	1.47	5.01	0.72	1.05	2.34	5.05	1.48	1.62	2.26
10	10.30	2.23	1.56	0.67	10.01	0.58	0.52	1.53	10.10	1.08	1.03	1.06
15	15.46	1.53	0.83	0.56	15.02	0.54	0.46	1.29	15.15	0.75	0.88	0.67
20	20.61	1.04	1.52	0.48	20.03	0.46	0.61	1.09	20.19	0.87	0.79	0.64

	RS 15				RS 18				RS 19			
Collector distance (m)	Drift distance (m)	Drift (%) Line A	Line B	Line C	Drift distance (m)	Drift (%) Line A	Line B	Line C	Drift distance (m)	Drift (%) Line A	Line B	Line C
0.5	0.52	2.21	0.16	0.39	0.52	22.23	6.97	6.50	0.52	5.78	10.87	2.21
1	1.05	1.00	0.11	0.17	1.04	5.67	2.14	2.44	1.04	1.93	2.69	0.93
2	2.10	0.36	0.11	0.31	2.07	1.94	0.65	0.87	2.08	0.60	0.29	0.65
3	3.15	0.34	0.09	0.26	3.11	1.01	0.54	0.71	3.13	0.52	0.24	0.40
5	5.24	0.18	0.10	0.36	5.19	0.53	0.39	0.42	5.21	0.42	0.17	0.22
10	10.49	0.11	0.04	0.09	10.37	0.36	0.36	0.33	10.42	0.09	0.10	0.12
15	15.73	0.08	0.04	0.05	15.56	0.37	0.36	0.33	15.63	0.08	0.07	0.09
20	20.98	0.06	0.04	0.04	20.74	0.34	0.32	0.31	20.84	0.06	0.09	0.08

	RS 21				RS 22				RS 23			
Collector distance (m)	Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)		
		Line A	Line B	Line C		Line A	Line B	Line C		Line A	Line B	Line C
0.5	0.53	0.96	15.01	1.60	0.53	4.58	8.25	14.49	0.51	6.63	27.77	14.21
1	1.05	0.56	5.70	2.71	1.05	2.27	4.16	5.97	1.01	2.29	20.29	11.78
2	2.10	0.42	0.32	2.78	2.11	0.83	1.63	3.09	2.02	3.73	6.02	2.58
3	3.16	0.29	1.43	0.39	3.16	0.36	2.76	1.40	3.03	1.42	14.14	1.34
5	5.26	0.27	0.27	0.31	5.27	0.48	0.77	1.00	5.05	0.09	3.31	3.75
10	10.52	0.07	0.09	0.16	10.54	0.16	0.58	0.58	10.10	0.85	1.19	5.34
15	15.78	0.06	0.07	0.10	15.82	0.12	0.14	0.14	15.16	0.20	0.19	0.70
20	21.04	0.08	0.05	0.07	21.09	0.10	0.10	0.23	20.21	0.11	0.17	0.19

	RS 24				RS 25				RS 26			
Collector distance (m)	Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)		
		Line A	Line B	Line C		Line A	Line B	Line C		Line A	Line B	Line C
0.5	0.51	13.24	25.88	24.23	0.55	32.93	4.60	45.62	0.50	34.85	6.01	72.97
1	1.01	9.25	17.83	8.62	1.10	12.47	2.50	11.46	1.01	16.72	2.33	31.10
2	2.03	4.19	6.37	3.62	2.21	6.25	1.75	4.57	2.02	6.73	1.30	13.56
3	3.04	2.45	3.05	2.00	3.31	4.36	1.92	2.13	3.03	7.16	1.02	6.77
5	5.07	1.50	1.35	1.26	5.52	2.00	1.97	1.07	5.04	3.06	0.73	3.06
10	10.15	0.64	0.67	0.65	11.03	0.76	0.80	0.63	10.09	0.69	0.50	1.19
15	15.22	0.50	0.55	0.53	16.55	0.67	0.46	0.47	15.13	0.57	0.42	0.65
20	20.29	0.41	0.43	0.50	22.07	0.42	0.39	0.35	20.17	0.46	0.37	0.47

	RS 27				**Average**		
Collector distance (m)	Drift distance (m)	Drift (%)			**Drift distance (m)**	**Drift (%)**	**sd**
		Line A	Line B	Line C			
0.5	0.50	20.00	12.49	32.40	**0.53**	**14.99**	**12.99**
1	1.00	6.68	2.93	9.54	**1.06**	**7.01**	**6.26**
2	2.01	1.15	1.93	1.94	**2.12**	**3.19**	**2.88**
3	3.01	0.83	1.56	0.85	**3.18**	**2.20**	**2.49**
5	5.02	0.73	1.05	0.74	**5.29**	**1.21**	**0.99**
10	10.04	0.53	0.63	0.62	**10.59**	**0.69**	**0.77**
15	15.06	0.47	0.47	0.45	**15.88**	**0.43**	**0.31**
20	20.08	0.44	0.42	0.45	**21.18**	**0.38**	**0.29**

5.3.1.3. Statistical drift prediction equation

Because of the obvious effect of the weather conditions on the amount of spray drift (Combellack *et al*., 1996; Miller *et al*., 2000 a; Thistle, 2000; Tsay *et al*., 2002 b), it is necessary to bring into account variations in atmospheric conditions when comparing measurements and to assess the contribution of the different meteorological parameters to the spray drift percentage at different distances. A multiple regression analysis was performed on the data (using SPSS 10.0.1) to develop a statistical drift prediction equation for the reference spraying with the amount of spray drift as the dependent variable.

Different dependent and independent variables were determined for each experiment as presented in Table 5.2: $RH_{1.25m}$, $RH_{2.15m}$, RH, $T_{1.25m}$, $T_{2.15m}$, T, $V_{1.50m}$, $V_{3.25m}$, V, $v_{1.50m}$, $v_{3.25m}$, v, δ, *A.S.*, *T.I.*, T_d, X_{H_2O}, drift distance and collector distance. Besides these first-order variables, different second-order combinations of these variables were also selected after a first statistical analysis and investigated. A forward stepwise regression procedure finally resulted in the following non-linear statistical drift prediction equation for the reference spraying with four independent, non-correlated variables:

$$drift_{\%} = (drift\_dist)^{-1.05} \times (13.00 + 0.50.V_{3.25m} + 0.40 \times T - 1.74 \times X_{H_2O}) \qquad (5.9)$$

With

$drift_{\%}$ – spray drift percentage expressed as a proportion of the application rate (%),
drift_dist – drift distance parallel with wind direction (m),
$V_{3.25m}$ – average wind speed at a height of 3.25 m (m.s^{-1}),
T – average temperature (°C),
X_{H_2O} – absolute humidity expressed in grams of water vapour per unit mass of dry air (g.kg^{-1}).

Hence, the four variables that were most significant in explaining the variation in spray drift percentages for the reference spraying were *drift_dist*, $V_{3.25m}$, T and X_{H_2O}.
A summary of the statistics of this regression is presented in Table 5.5. An R^2 of 0.84 is obtained using the average of the three sampling lines as the dependent variable. With a similar approach but for different application techniques using five independent variables and a linear regression analysis, Bode *et al*. (1976) found R^2 values of only 0.56.

Table 5.5: Non-linear regression statistics

Source of Variation	Sum of squares (SS)	df	Mean square (MS)	Variable	Coefficient	SE	T	Prob. > |T|
Regression	SSR = 19088.7	5	MSR = 3817.7	*drift_dist*	-1.05	0.04	-25.6	<0.00001
Error	SSE = 3115.0	451	MSE = 7.4	Constant	13.00	0.63	20.6	<0.00001
Total	SSTO = 22403.7	456		$V_{3.25m}$	0.50	0.12	4.13	0.00004
				T	0.40	0.05	7.62	<0.00001
	$R^2 = 1 - \frac{SSE}{SSTO} = 0.84$			X_{H_2O}	-1.74	0.11	-16.0	<0.00001

df, degrees of freedom; SE, standard error; SSR, sum of squares of regression; MSR, mean square of regression; SSE, sum of squares of error, MSE, mean square of error; SSTO, total sum of squares; *drift_dist*, drift distance; $V_{3.25m}$, average wind speed at a height of 3.25 m; T, average temperature; X_{H_2O}, absolute humidity; T, T for H_0: coefficient = 0

As described in section 1.4, Rautmann *et al*. (2001), Kaul *et al*. (1996 b) and Carlsen *et al*. (2006 b) also found that a power function is suitable as drift prediction equation but they did not bring into account meteorological factors.

5.3.1.4. Discussion of the drift equation

With this drift prediction equation, it is possible to predict the amount of spray drift deposition on grassland for the reference spray application technique under various atmospheric conditions for drift distances up to at least 20 metres by measuring wind speed, humidity and temperature. Based on the available drift data, the equation is usable for temperatures varying from about 8°C to 30°C, absolute humidities from about 3.5 to 12 $g.kg^{-1}$ and wind speeds from about 1 $m.s^{-1}$ to 6 $m.s^{-1}$ but only for realistic combinations of temperature and absolute humidity.

Some drift curves based on the drift equation for the reference spraying on a meadow are presented in Figure 5.8, Figure 5.9 and Figure 5.11, each time starting from standard meteorological conditions defined as a temperature of 16°C in combination with an absolute humidity of 8 $g.kg^{-1}$ and a wind speed of 3 $m.s^{-1}$. A logarithmic scale is used for the X-axis. The same results can be found in Annex 12 but presented with a logarithmic Y-axis which gives a more detailed view on long distance drift.

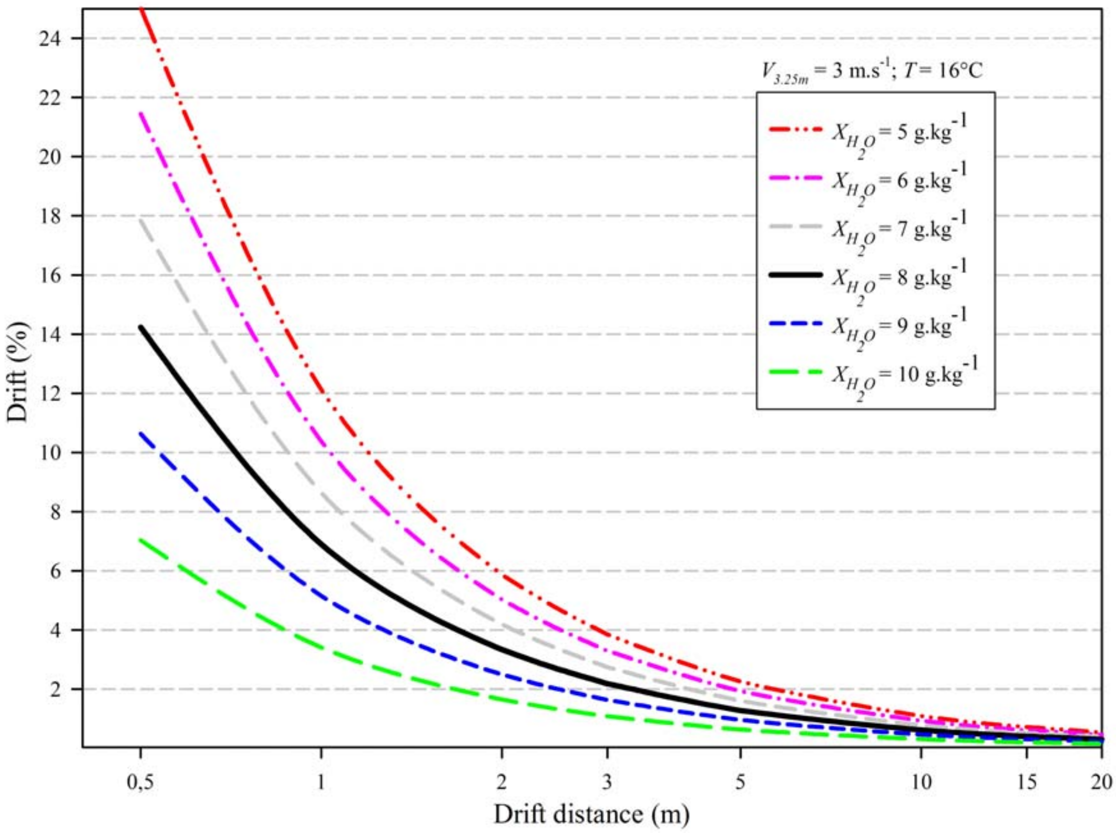

Figure 5.8: Predicted drift curves for the reference spraying on a meadow for absolute humidities (X_{H_2O}) varying from 5 to 10 $g.kg^{-1}$ in combination with an average temperature (T) of 16°C and a wind speed of 3 $m.s^{-1}$ at a height of 3.25 m ($V_{3.25m}$)

The effect of absolute humidity (varying from 5 to 10 $g.kg^{-1}$) on the amount of spray drift for the reference spraying at a temperature of 16°C and a wind speed of 3 $m.s^{-1}$ is shown in

Figure 5.8. For example, a decrease in absolute humidity from 9 to 6 g.kg^{-1} doubles the amount of spray drift at a constant temperature and wind speed. In most cases, absolute humidity was situated between 6 and 10 g.kg^{-1}. Regarding meteorological conditions, absolute humidity has the most important impact on the amount of spray drift. The lower the absolute humidity, the higher the amount of drift due to the effect of evaporation which reduces droplet size as reported among others by Bache and Johnston (1992), Miller (1993), Kincaid and Longley (1989). At a temperature of 16°C, absolute humidities of 5, 6, 7, 8, 9 and 10 g.kg^{-1} correspond with relative humidities of, respectively, 45, 53, 62, 71, 80 and 88%.

Besides a lower humidity of the air, a higher temperature also raises the amount of droplet evaporation (Elliott & Wilson, 1983) and hence the amount of spray drift. This is illustrated in Figure 5.9 for temperatures varying from 12°C to 28°C at a wind speed of 3 m.s^{-1} and an absolute humidity of 8 g.kg^{-1}. From this graph, it can be concluded that an increase in temperature from 12 to 24 °C, at a constant absolute humidity and wind speed, almost doubles the amount of spray drift. Different authors have discussed the importance of temperature in relation to pesticide drift (Goering & Butler, 1975; Bode *et al*., 1976; Smith *et al*., 1982 b).

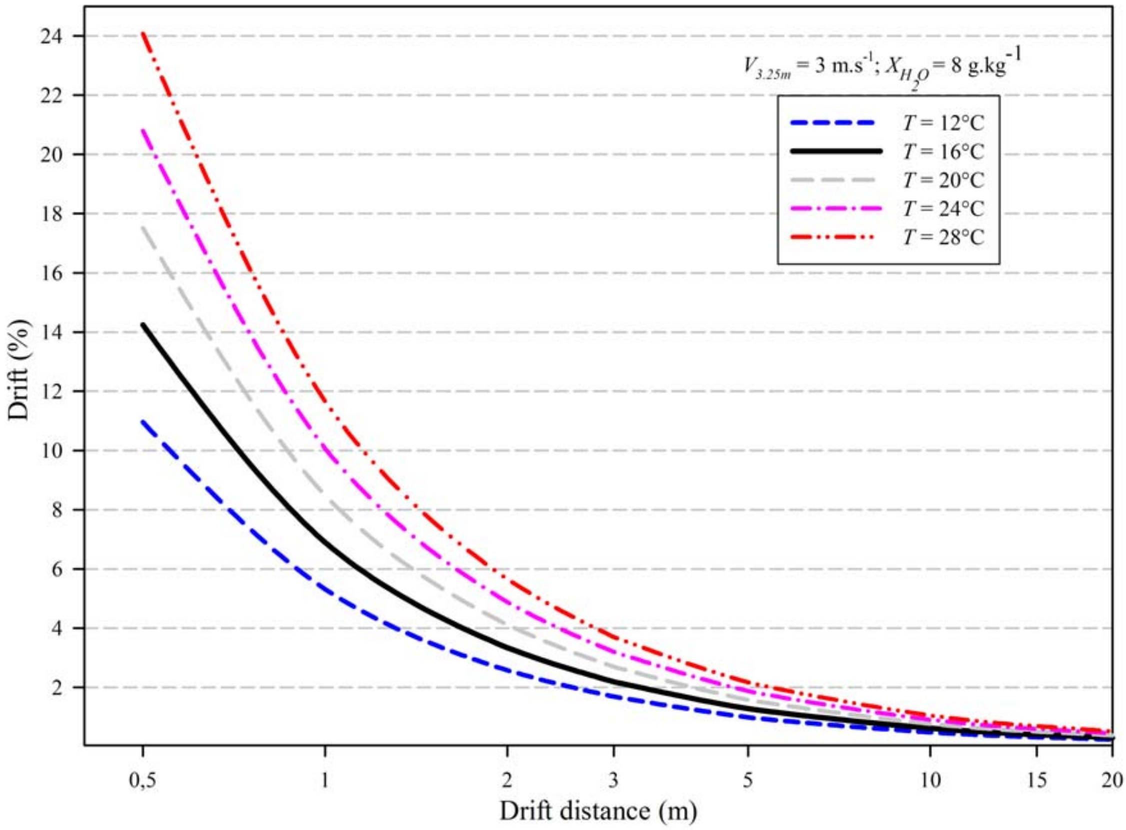

Figure 5.9: Predicted drift curves for the reference spraying on a meadow for average temperatures (*T*) varying from 12°C to 28°C at a wind speed of 3 m.s^{-1} at a height of 3.25 m ($V_{3.25m}$) and an absolute humidity (X_{H_2O}) of 8 g.kg^{-1}

In this context, it is important to realise that humidity of the air is often expressed in terms of relative humidity which is closely linked to temperature. As the temperature of air increases, its capacity to contain water vapour increases and hence relative humidity decreases inversely but non-linearly for a given constant absolute humidity and the amount of spray drift increases as illustrated in Figure 5.8. Similarly, an increase in absolute humidity results in a proportional increase in relative humidity. Because of the relation between relative humidity and temperature on the one hand, and absolute humidity on the other hand, a decrease in relative humidity always results in an increase of the amount of spray drift. This relation between relative humidity, temperature and absolute humidity is illustrated in Figure 5.10 together with the measuring data from the different reference sprayings.

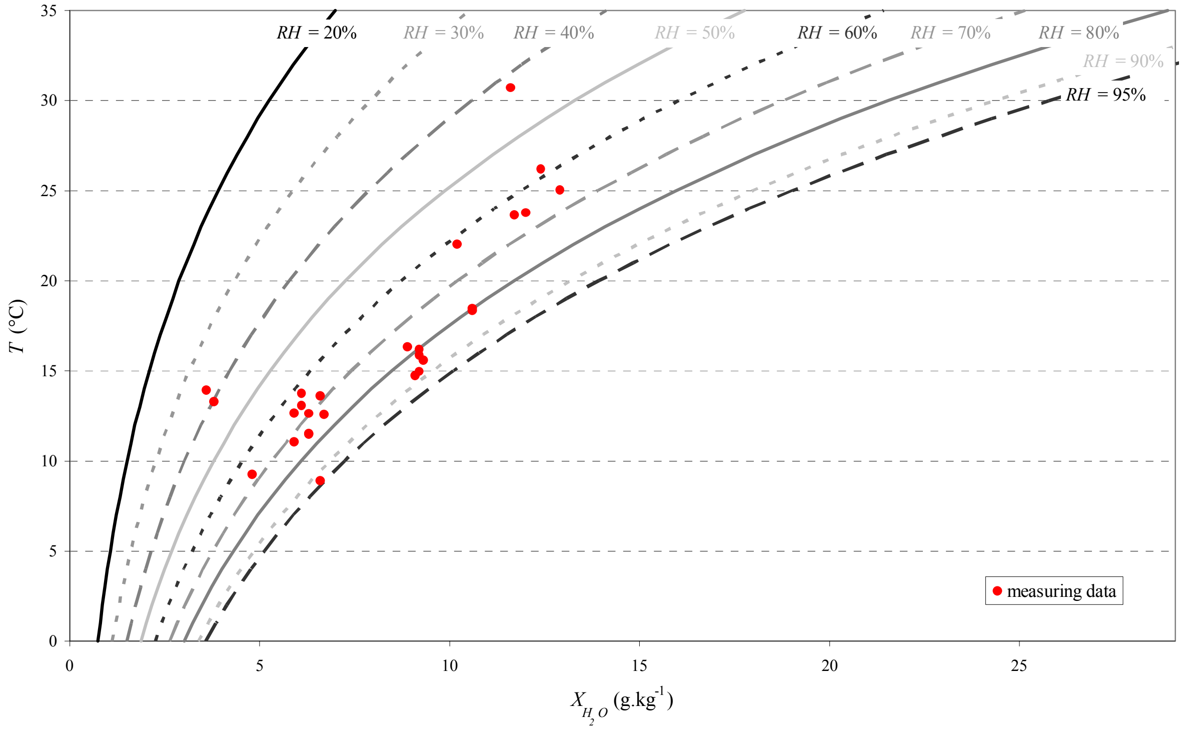

Figure 5.10: Relation between relative humidity (*RH*), temperature (*T*) and absolute humidity (X_{H_2O}) together with the measuring data from the different reference sprayings

Although the physical principles of drop evaporation in pesticide application have been well described in the bibliographic resources for several decades (Goering *et al*., 1972; Williamson & Threadgill, 1974), the rate of evaporation in agricultural spraying technology continues to be a complex problem that involves physical and chemical properties of spray liquid and drop surrounding air conditions (temperature and humidity). The reason for this is the possible addition of non-volatile compounds which changes the behaviour of drop evaporation (Reichard *et al*., 1992 a; Hall *et al*., 1994). The spray liquid used in these experiments has constant properties representative of liquids typically used in the application of plant protection products.

For the experimental set-up used in this research, the effect of absolute humidity and temperature on the amount of spray drift is even more important than the effect of the wind speed as presented in Figure 5.11. For example, an increase in wind speed from 1 to 6 m.s^{-1} increases the amount of spray drift from 2.86 to 4.07% at a distance of 2 m and from 1.10 to 1.56% at a distance of 5 m for the reference spraying at an absolute humidity of 8 g.kg^{-1} and a temperature of 16°C. Logically, higher wind speeds result in higher amounts of spray drift but the effect of the wind speed on the amount of sedimenting spray drift is less pronounced compared to the effect of relative humidity and compared with the results from other researchers (Combellack *et al*., 1996; Yates *et al*., 1967; Maybank *et al*., 1978; Crabbe *et al*., 1994). For example, Nordby and Skuterud (1975) found that an increase in wind speed from 1.5 m.s^{-1} to 4.0 m.s^{-1} increased the drift by a factor 2 and a number of wind tunnel and field studies showed a comparable approximately linear relationship between spray drift and wind speed, but the effect of other atmospheric conditions (e.g. temperature and humidity) was not taken into account in most studies (Gilbert & Bell, 1988; Western *et al*., 1989; Hobson *et al*., 1990; Carlsen *et al*., 2006 b). However, others like Heijne *et al*. (2002) even did not observe any effect of wind speed on drift deposits based on a limited number of experiments with orchard sprayers.

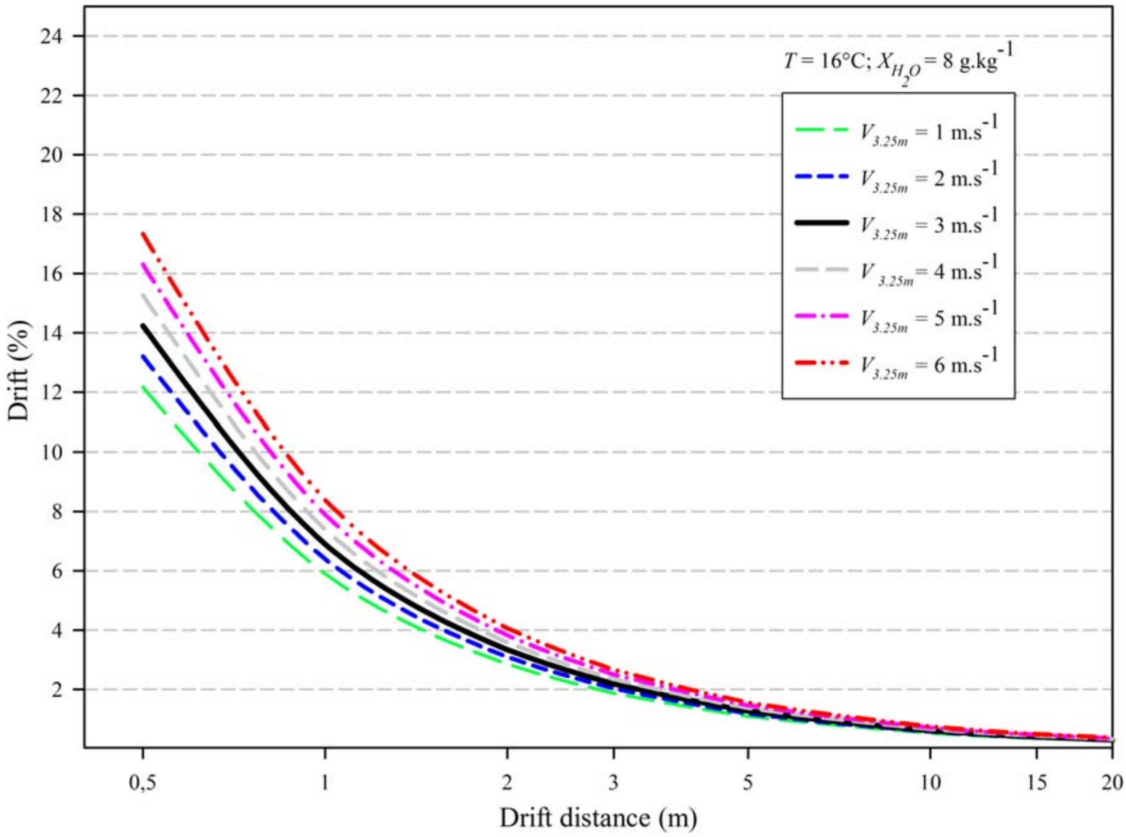

Figure 5.11: Predicted drift curves for the reference spraying on a meadow for wind velocities at a height of 3.25 m ($V_{3.25m}$) varying from 1 to 6 m.s^{-1} in combination with an average temperature (*T*) of 16°C and an absolute humidity (X_{H_2O}) of 8 g.kg^{-1}

In accordance with Smith *et al*. (1982 b), the atmospheric stability was not found to be a significant drift-related variable but it is important to keep in mind that most of the treatments were carried out under unstable conditions. Bode *et al*. (1976) noted that wind speed was more important than stability under unstable conditions when drift from ground sprayers was measured. Rutherford *et al*. (1989) also reported no improvement in the correlation between measured drift and wind speed when atmospheric stability was included in the analysis. Moreover, different authors found that stability effects are more important in the far field once the spray cloud is airborne but the drift measurements in this study were limited up to 20 m (Yates *et al*., 1967; Maybank *et al*., 1978; Crabbe *et al*., 1994).

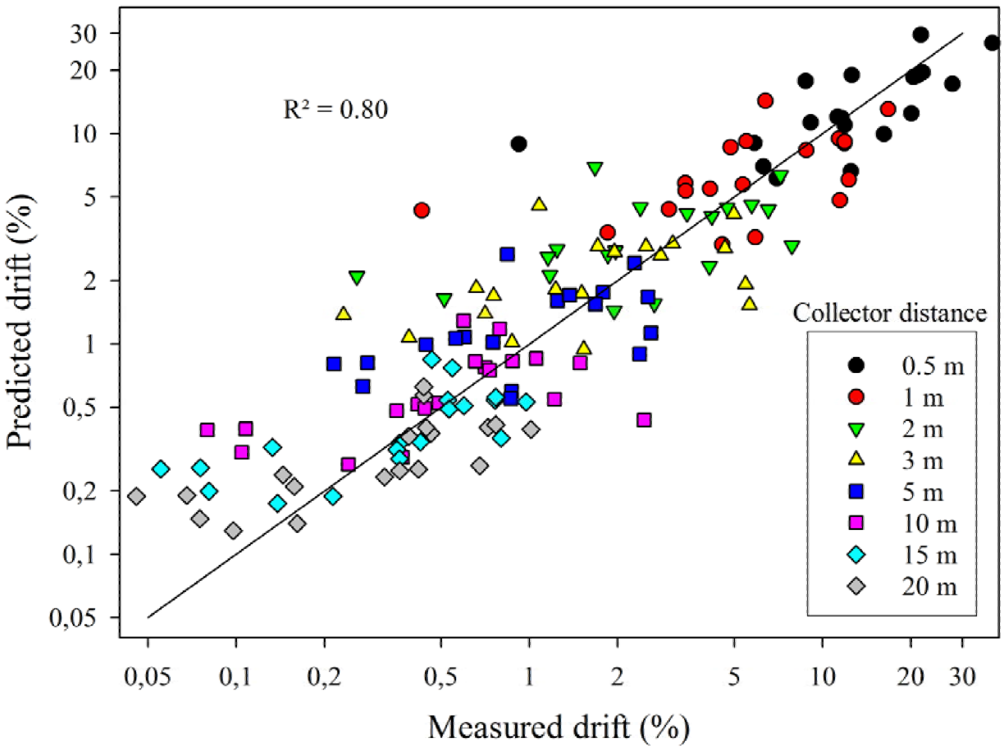

Figure 5.12: Comparison between average measured drift values and predicted drift values specifying the collector distances

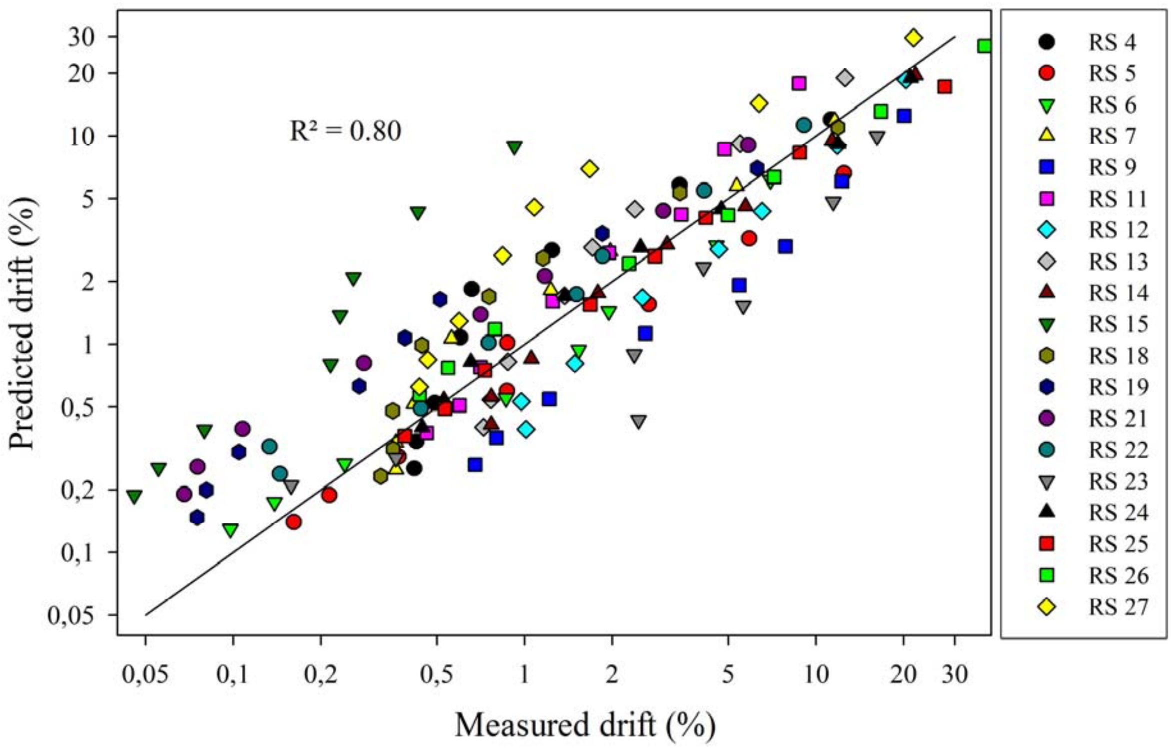

Figure 5.13: Comparison between average measured drift values and predicted drift values specifying the experiments

In Figure 5.12 and Figure 5.13, a comparison is made between measured and predicted drift values, using the corresponding weather conditions (T, X_{H_2O} and $V_{3.25m}$) and specifying the collector distances (Figure 5.13) and the experiments (Figure 5.12). In general, the correlation between measured and predicted drift values is satisfying ($R^2 = 0.80$). Considering the collector distance, the drift equation gives a little overestimation for high collector distances corresponding with very small measured drift values (< 0.2%). For some specific experiments, the drift equation gives a small global underestimation (e.g. RS 9 & RS 23) or overestimation (e.g. RS 15 & RS 27) compared to the measured values. These deviations can be attributed to factors like deviation of spray boom height, spray line and spray boom movements. Finally, the predicted drift curves for the weather conditions corresponding with the different reference sprayings (RS) are presented in Annex 13.

5.3.1.5. Validation of the drift equation

Five reference sprayings (RS_v) were carried out to validate the drift prediction equation 5.9 discussed in section 5.3.1.4 at different atmospheric conditions as presented in Table 5.6. For RS_v 1, 2 and 3, absolute humidity and temperature were low resulting in a very low dew-point temperature.

Table 5.6: Most important meteorological variables for the different reference experiments used to validate the drift prediction equation (RS_v)

Experiment	RH (%)	X_{H_2O} ($g.kg^{-1}$)	T (°C)	$V_{1.50m}$ ($m.s^{-1}$)	$V_{3.25m}$ ($m.s^{-1}$)	V ($m.s^{-1}$)	δ (°)	$A.S.$ ($°C.m^{-1}$)	$T.I$	T_d (°C)
RS_v 1	58.0	3.1	4.7	3.97	4.05	4.01	16.1	-0.49	0.51	-2.9
RS_v 2	53.9	3.0	5.6	2.75	3.00	2.88	8.6	-0.50	0.48	-3.0
RS_v 3	71.1	4.2	6.3	4.90	5.64	5.27	11.4	-0.07	0.62	1.5
RS_v 4	83.5	6.4	10.0	3.67	4.28	3.98	25.0	-0.22	0.55	7.4
RS_v 5	64.0	8.2	18.0	2.72	3.13	2.93	5.0	-0.23	0.68	11.1

RH, average relative humidity; X_{H_2O}, Absolute humidity; *T*, average temperature; $V_{1.50m}$, average wind speed at 1.50 m; $V_{3.25m}$, average wind speed at 3.25 m; *V*, average wind speed; δ, deviation of ideal driving direction; *A.S.*, atmospheric stability; *T.I.*, turbulence intensity; T_d, dew-point temperature; RS_v, reference spraying used for validation

Using drift prediction equation 5.9, sedimenting drift values were calculated for meteorological conditions (T, X_{H_2O} and $V_{3.25m}$) corresponding with reference sprayings RS_v 1 to 5. In Figure 5.14, the measured sedimenting spray drift results from reference sprayings RS_v 1, RS_v 3 and RS_v 5 are presented with their 90% confidence intervals together with the predicted drift values for the corresponding atmospheric conditions. Note the logarithmic scale of the X-axis. The same results are presented in Figure 5.15 for reference sprayings RS_v 2, RS_v 3 and RS_v 4, this time with a logarithmic scale of the Y-axis. From these figures, it is clear that almost all predicted sedimenting drift values are situated within the 90% confidence intervals based on the measured drift values. The good predictive power of the drift prediction equation is confirmed in Figure 5.16 comparing measured drift values and predicted drift values for the different RS_v experiments. The correlation between predicted and measured values is significant at the 0.01 level with a Pearson coefficient of correlation of 0.96 and an R^2 of 0.95, indicating the good predictive power of the drift equation.

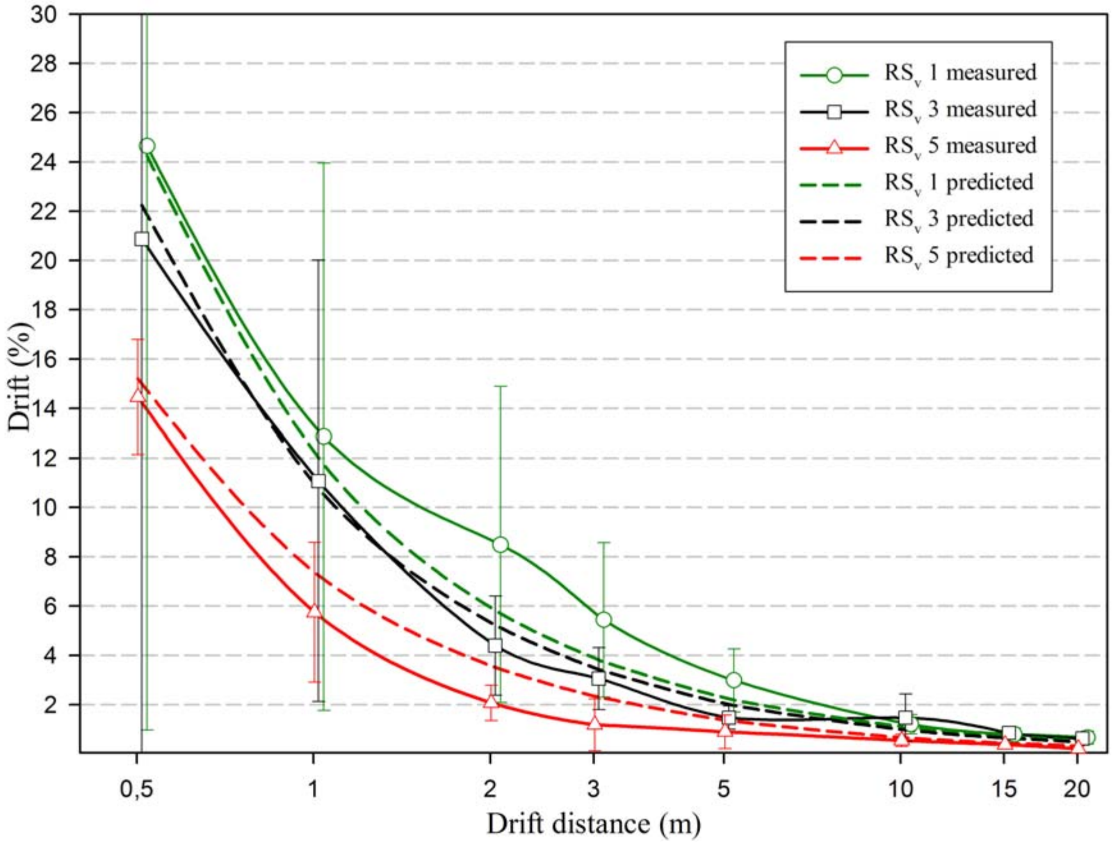

Figure 5.14: Measured and predicted drift data and 90% confidence intervals for reference sprayings RS_v 1, RS_v 3 and RS_v 5

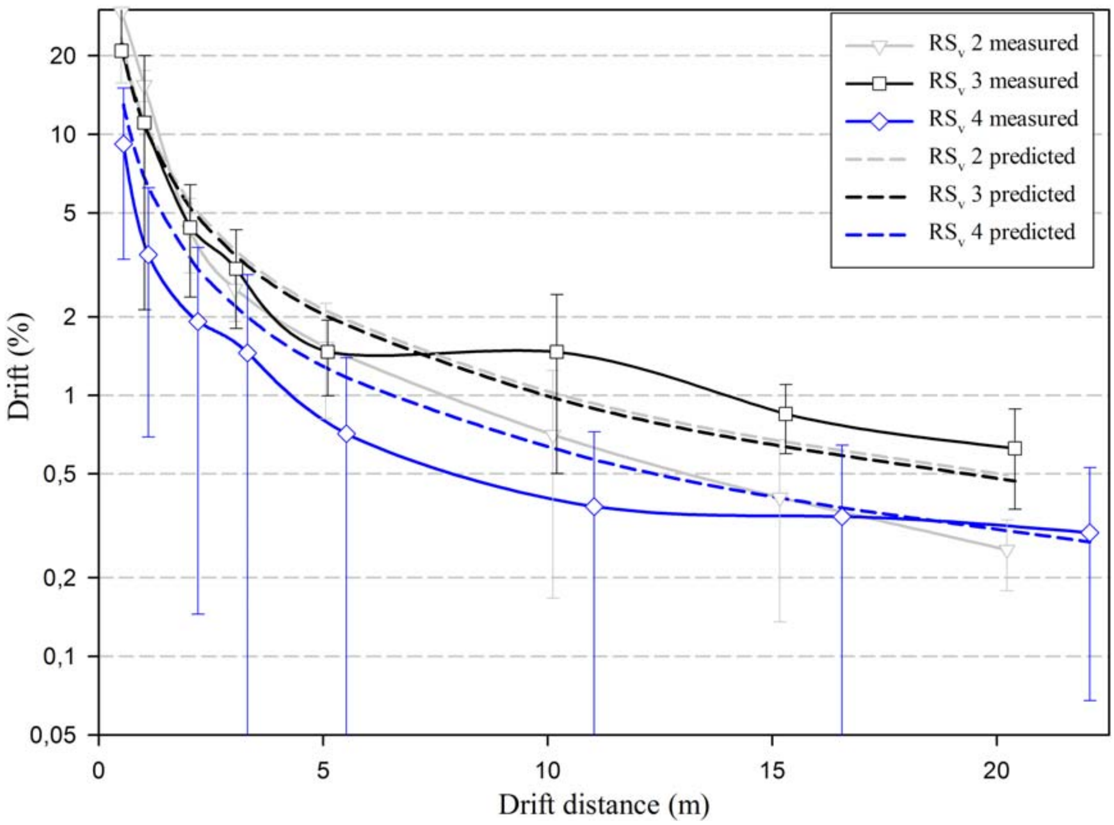

Figure 5.15: Measured and predicted drift data and 90% confidence intervals for reference sprayings RS_v 2, RS_v 3 and RS_v 5

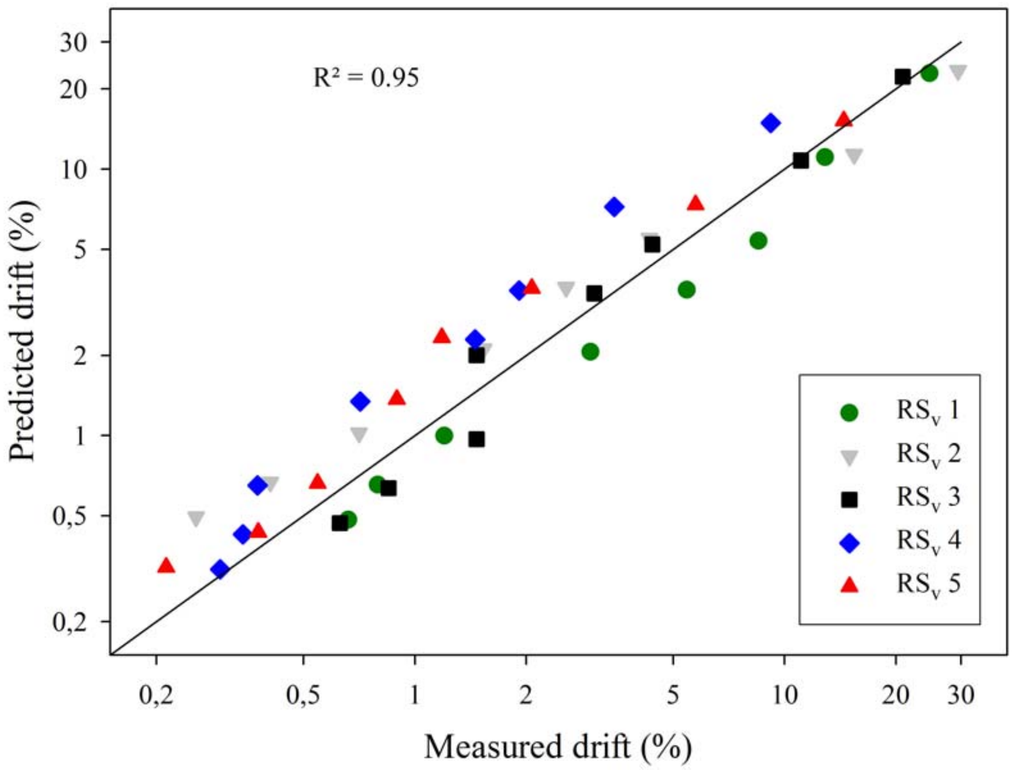

Figure 5.16: Comparison between average measured drift values and predicted drift values for the RS_v experiments

Table 5.7: Sedimenting drift data of the 5 reference sprayings (RS_v) used for validation

	RS_v 1				RS_v 2				RS_v 3			
Collector distance (m)	Drift distance (m)	Drift (%) Line A	Line B	Line C	Drift distance (m)	Drift (%) Line A	Line B	Line C	Drift distance (m)	Drift (%) Line A	Line B	Line C
0.5	0.5	22.03	46.74	5.15	0.5	41.63	17.33	29.39	0.5	45.52	11.86	5.23
1	1.0	12.14	23.01	3.44	1.0	17.55	14.56	14.17	1.0	20.04	8.03	5.14
2	2.1	6.76	14.81	3.89	2.0	5.70	3.71	3.53	2.0	6.05	4.60	2.52
3	3.1	4.32	8.59	3.40	3.0	2.75	1.92	3.01	3.1	4.00	3.33	1.84
5	5.2	2.49	4.27	2.19	5.1	2.24	1.02	1.33	5.1	1.94	1.15	1.31
10	10.4	1.04	1.60	0.96	10.1	0.49	0.38	1.25	10.2	1.16	2.43	0.81
15	15.6	0.73	1.04	0.61	15.2	0.30	0.24	0.68	15.3	1.10	0.75	0.70
20	20.8	0.65	0.90	0.43	20.2	0.28	0.18	0.31	20.4	0.80	0.72	0.36

	RS_v 4				RS_v 5			
Collector distance (m)	Drift distance (m)	Drift (%) Line A	Line B	Line C	Drift distance (m)	Drift (%) Line A	Line B	Line C
0.5	0.55	15.15	6.37	6.02	0.5	16.76	12.80	13.83
1	1.10	6.29	2.01	2.08	1.0	5.65	8.30	3.29
2	2.21	3.72	1.10	0.93	2.0	2.55	2.31	1.35
3	3.31	2.92	0.64	0.80	3.0	0.56	2.25	0.74
5	5.52	1.51	0.31	0.31	5.0	0.46	1.58	0.64
10	11.04	0.99	0.09	0.04	10.0	0.63	0.71	0.30
15	16.55	0.86	0.11	0.06	15.1	0.42	0.43	0.28
20	22.07	0.74	0.10	0.06	20.1	0.16	0.32	0.16

5.3.2. Other spray application techniques

5.3.2.1. Drift reduction potential

Besides the reference sprayings (RS & RS_v), different other sprayings (OS) were performed for 20 different combinations (identified as A up to T) of nozzle type (standard flat fan, low-drift, air inclusion) and size (ISO 02, 03, 04 and 06), spray pressure (2, 3 and 4 bar), driving speed (4, 6, 8 and 10 $km.h^{-1}$), spray boom height (0.3, 0.5 and 0.75 m) and with and without the use of air assistance (Table 5.1). The reference spraying is defined as a standard horizontal spray boom without air assistance, a spray boom height of 0.50 m, a nozzle distance of 0.50 m, ISO 110 03 standard flat fan nozzles at 3.0 bar (1.2 $L.min^{-1}$) and a driving speed of 8 $km.h^{-1}$, resulting in an application rate of approximately 180 $L.ha^{-1}$.

The drift results of the other sprayings (OS) are compared with the reference spraying (RS) by calculating their drift reduction potential (*DRP*). This *DRP* is expressed as the percentage of drift reduction compared with the reference spraying at a certain drift distance. These percentages are calculated by comparing the measured OS drift values ($drift_{OS}$) with the RS drift values ($drift_{RS}$) predicted by means of the drift prediction equation 5.9 **for the same meteorological conditions** using the following formula:

$$DRP = \frac{(drift_{RS} - drift_{OS})}{drift_{RS}}.100 \qquad (5.10)$$

With

DRP – drift reduction potential (%),
$drift_{OS}$ – measured other spraying drift value (%),
$drift_{RS}$ – predicted reference spraying drift value (%).

Hence, this approach is an alternative for the dual tracer technique, which compares two separate spraying systems mounted on the same tractor, as proposed by Courshee (1959) and Bode *et al*. (1976) to compare the amount of drift of different systems relatively. With this approach it is possible to predict the expected magnitude of drift at various weather conditions.

By means of numerical integration, the total drift reduction potential (DRP_t, %) of a specific spraying is calculated by comparing the surface under the measured drift curve of this spraying with the surface under the predicted drift curve of the reference spraying, again for the same weather conditions. This variable expresses the total amount of drift reduction of a specific spraying compared with the reference spraying. For the calculation of *DRP* and DRP_t, average values of the three collector lines are used.

Using drift equation 5.9 for the reference spraying on the one hand, and *DRP* values of the other sprayings on the other hand, expected sedimenting drift values at different distances can be determined for the different other spray application techniques for any weather condition within the range of the drift prediction equation.

5.3.2.2. Atmospheric conditions

An overview of the most important meteorological variables influencing spray drift, i.e. average temperature (T), average wind speed at a height of 3.25 m ($V_{3.25m}$), absolute humidity (X_{H_2O}), and the deviation of the ideal driving direction on wind direction (δ), for the 76 other sprayings (OS) are presented in Table 5.8. A more detailed overview can be found in Annex 14.

In 11 cases, δ exceeded 40° to the average wind direction. These experiments were not analyzed, but still, for each type of experiment (A – T) at least three successful repetitions were carried out except for experiment G with only two successful measurements. This results in 65 useful drift trials corresponding with 1560 sedimenting drift measurements. In Figure 5.17, the range of average temperature (T), average wind speed at a height of 3.25 m ($V_{3.25m}$) and absolute humidity (X_{H_2O}) is presented for the different other sprayings as well as for the reference sprayings by means of boxplots. It is clear that these ranges are quite similar and the range of meteorological conditions of the other sprayings is situated within the range of the reference sprayings. Hence, drift prediction equation 5.9 is valid for the different weather conditions. Average values of T, $V_{3.25m}$ and X_{H_2O}, respectively 17.2°C, 3.37 m.s^{-1} and 8.4 g.kg^{-1}, are close to the standard meteorological conditions defined as a temperature of 16°C in combination with an absolute humidity of 8 g.kg^{-1} and a wind speed of 3 m.s^{-1}

Measurements were carried out at the end of August - beginning of September 2004, May 2005 and the end of March – beginning of April 2006 with a total of 21 measuring days and measurements were carried out during the entire day. In accordance with the reference spraying, most of the experiments (64 treatments out of 76) were carried out under unstable conditions illustrated by a negative sign of the *A.S.* value (Annex 14).

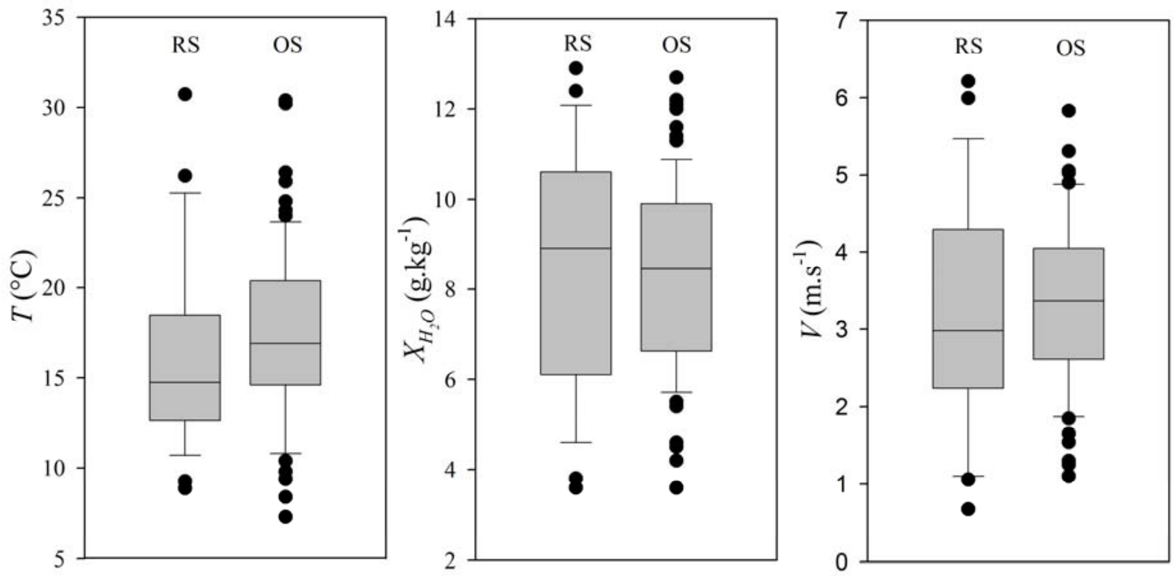

Figure 5.17: Range of average temperature (T), absolute humidity (X_{H_2O}) and wind velocity (V) measured during the 27 reference sprayings (RS) and the 76 other sprayings (OS). Boxplots show the 10th, 25th, 50th, 75th and 90th percentile of the measuring data

Table 5.8: Most important meteorological variables for the different other sprayings (OS)

Experiment	T (°C)	$V_{3.25m}$ (m.s^{-1})	X_{H_2O} (g.kg^{-1})	δ (°)	Experiment	T (°C)	$V_{3.25m}$ (m.s^{-1})	X_{H_2O} (g.kg^{-1})	δ (°)
A 1	20.5	4.17	10.0	17.3	L 1	19.1	1.25	8.6	65.6[a]
A 2	20.3	2.82	10.4	0.5	L 2	18.4	4.54	8.4	36.5
A 3	20.4	3.95	9.9	15.1	L 3	23.2	4.19	8.5	34.4
B 1	15.7	4.63	9.8	27.5	L 4	11.3	4.07	7.3	50.7[a]
B 2	17.5	3.13	10.5	10.8	L 5	17.1	2.60	9.4	32.7
B 3	17.0	3.29	9.7	6.1	L 6	14.7	2.65	8.0	8.3
C 1	17.3	1.88	10.7	16.2	M 1	19.7	1.30	8.7	94.6[a]
C 2	17.4	3.50	10.6	7.3	M 2	19.5	4.51	8.5	41.5[a]
C 3	18.2	3.38	10.0	18.8	M 3	23.5	3.83	8.4	36.9
D 1	16.7	3.67	9.9	14.8	M 4	11.7	4.27	7.3	29.1
D 2	17.5	4.79	9.4	4.5	M 5	16.1	2.89	8.3	0.9
D 3	9.4	1.99	6.4	20	N 1	16.8	3.61	8.4	28.3
E 1	19.0	5.05	8.7	2.2	N 2	22.4	4.87	8.4	24.8
E 2	20.8	4.90	9.8	32.6	N 3	24.0	5.83	7.7	41.7[a]
E 3	20.2	5.31	9.3	20.2	N 4	15.5	3.58	8.2	8.5
F 1	14.6	1.10	6.5	74.3[a]	O 1	21.0	2.52	9.6	12
F 2	15.3	3.10	5.8	32.5	O 2	25.9	5.04	12.7	28.5
F 3	10.4	3.37	7.1	32.2	O 3	13.3	1.54	6.2	16.2
F 4	16.6	1.97	7.0	3.3	P 1	24.8	3.30	12.1	31.6
G 1	15.6	2.80	6.1	20.8	P 2	12.8	1.65	6.4	96.3[a]
G 2	14.7	1.65	6.0	35.2	P 3	14.5	3.92	5.4	10.3
G 3	10.8	5.03	7.2	48.2[a]	P 4	16.0	3.41	9.1	10.5
H 1	15.0	3.31	5.5	93.5[a]	Q 1	20.8	3.64	10.4	25.2
H 2	14.7	3.82	5.8	12.5	Q 2	21.4	1.91	10.5	18.8
H 3	11.1	4.04	7.2	39.8	Q 3	22.4	3.36	10.6	11.7
H 4	16.4	2.49	7.2	22.8	Q 4	22.9	1.97	11.3	19.8
I 1	18.5	3.62	9.8	26.7	Q 5	24.3	2.36	12.0	34.6
I 2	19.1	3.80	9.9	20.2	R 1	9.8	4.46	4.6	9.2
I 3	20.5	3.07	10.3	34	R 2	10.8	4.05	4.6	22.2
J 1	14.6	3.04	9.4	25.2	R 3	13.5	2.66	3.6	17.5
J 2	14.9	2.98	9.4	4.1	S 1	26.4	2.49	12.2	70.4[a]
J 3	15.0	2.88	9.4	18	S 2	30.2	3.14	11.6	38.1
K 1	17.9	3.90	8.5	45.3[a]	S 3	30.4	3.91	11.4	28.2
K 2	17.1	3.01	7.8	37.6	S 4	14.0	3.08	8.2	33.7
K 3	17.1	3.68	8.3	34.2	S 5	16.8	3.68	7.4	12.7
K 4	14.2	5.83	6.4	16.2	T 1	9.8	2.60	6.5	22.6
K 5	13.0	4.86	6.1	35.3	T 2	7.3	1.85	4.2	20.8
K 6	14.6	3.33	6.0	2.7	T 3	8.4	2.25	4.5	21.8
					Average	**17.2**	**3.37**	**8.4**	**28.0**

[a] Deviation of ideal driving direction > 40°; T, average temperature; $V_{3.25m}$, average wind speed at 3.25 m; X_{H_2O}, absolute humidity; δ, deviation of ideal driving direction

5.3.2.3. Sedimenting drift data

A complete overview of the sedimenting spray drift results from the different experiments with other spray application techniques is presented in Annex 15 and discussed in sections 5.3.2.4 up to 5.3.2.9.

5.3.2.4. Effect of nozzle type

Drift reduction potentials (*DRP*) for different nozzle types (standard flat fan, low-drift flat fan and air inclusion nozzles) and sizes (ISO 02, 03 and 04) are presented for different collector distances in Figure 5.18 and total drift reduction potentials (DRP_t) in Figure 5.19 together with the standard deviations. A complete overview of *DRP* and DRP_t values and their standard deviations is presented in Annex 16. All sprayings were carried out at a driving speed of 8 km.h^{-1}, a spray pressure of 3.0 bar and with a boom height of 0.50 m and the reference nozzle is defined as a Hardi ISO F 110 03 flat fan nozzle. The results are based on experiments A to H (Table 5.1). Based on these *DRP* values and drift equation 5.9 for the reference spraying, expected sedimenting drift curves for these nozzle types can be determined for any weather condition within the range of the drift prediction equation. This is presented in Figure 5.20 for standard meteorological conditions (T= 16°C, $V_{3.25m}$= 3 m.s^{-1} and X_{H_2O}= 8 g.kg^{-1}) with a logarithmic scale of the X-axis.

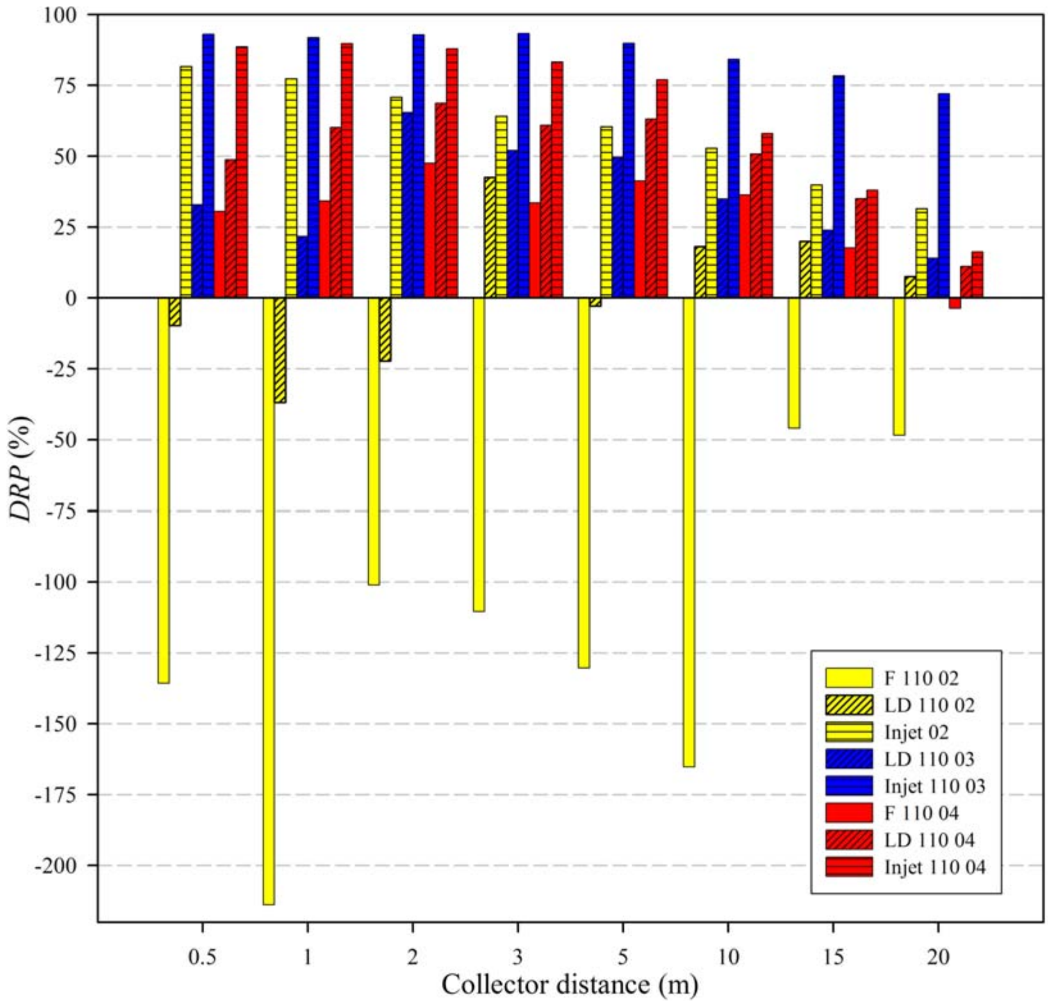

Figure 5.18: ***DRP*** **values at different distances for different Hardi ISO nozzle types (F: standard flat fan, LD: low-drift, Injet: air inclusion) and sizes (ISO 02, 03 and 04) compared to the reference (Hardi ISO F 110 03 standard flat fan) at a pressure of 3.0 bar**

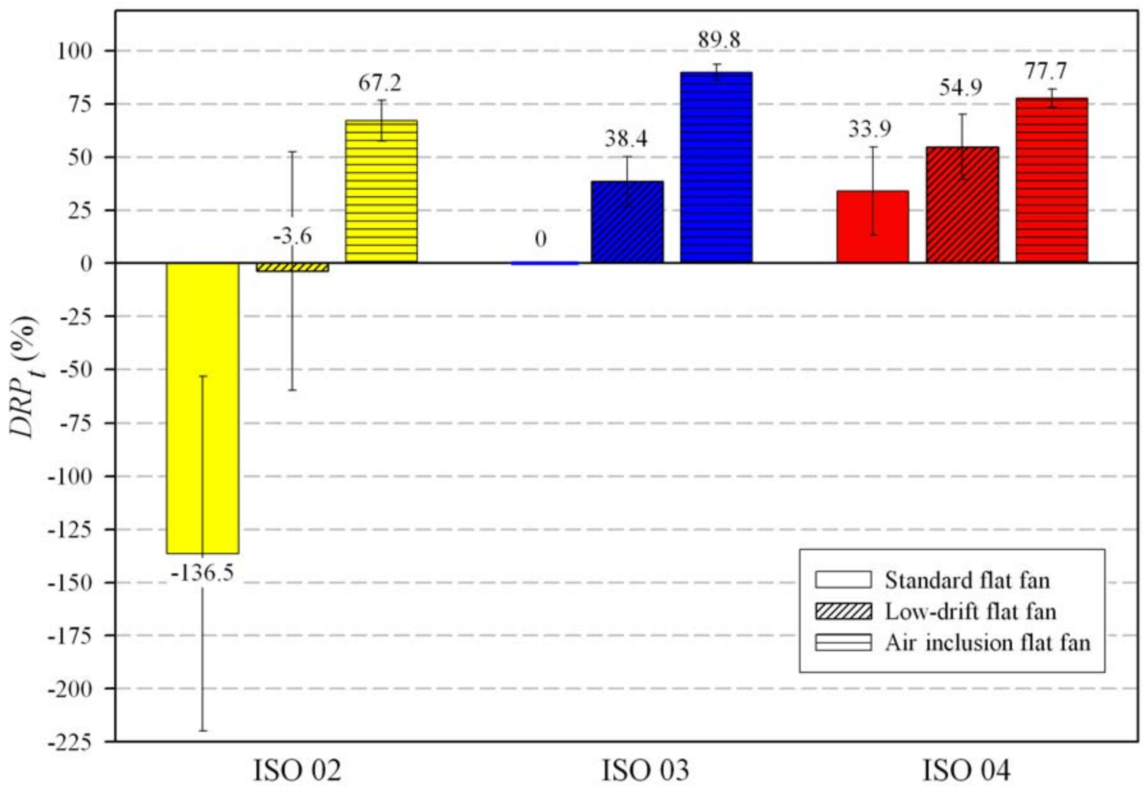

Figure 5.19: DRP_t values and standard deviations for different Hardi ISO nozzle types and sizes compared to the reference (Hardi ISO F 110 03 standard flat fan) at a spray pressure of 3.0 bar

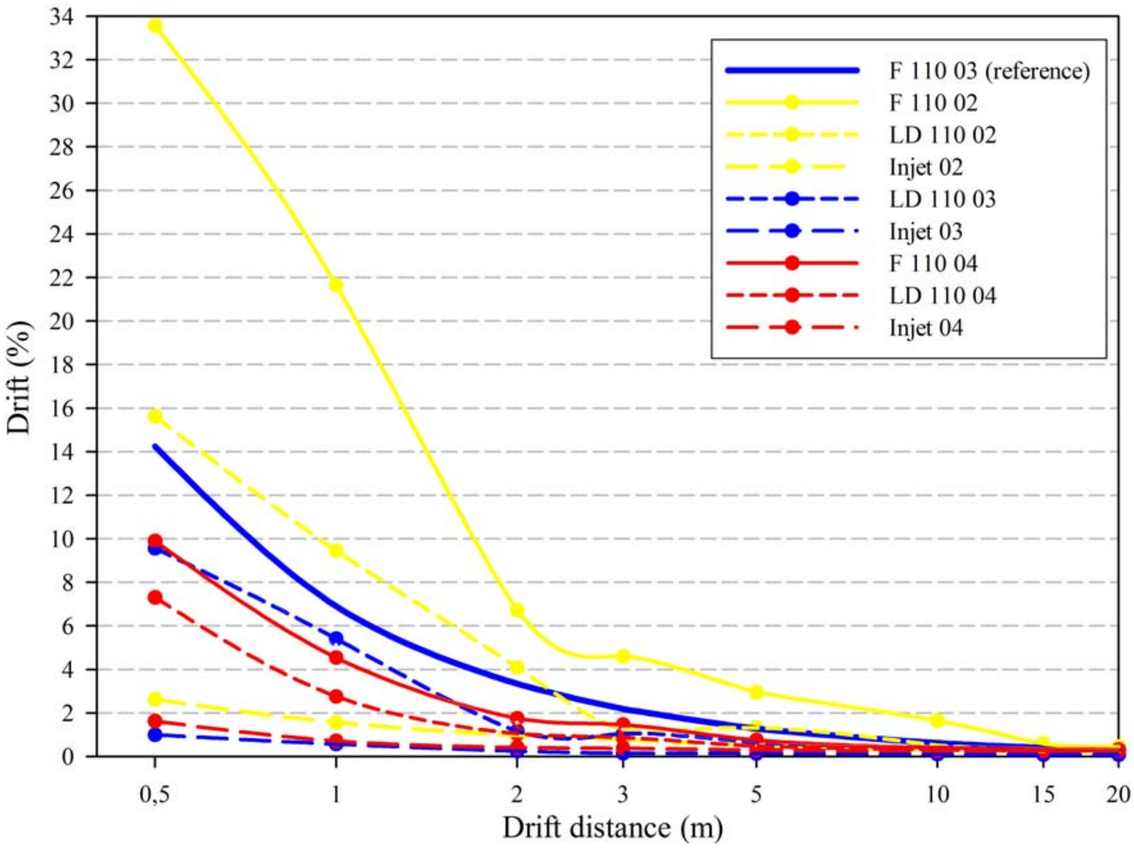

Figure 5.20: Predicted sedimenting drift curves for different Hardi ISO nozzle types and sizes at a spray pressure of 3.0 bar and standard meteorological conditions (T = 16°C, $V_{3.25m}$= 3 m.s^{-1} and X_{H_2O}= 8 g.kg^{-1}) with a logarithmic scale of the X-axis

It is clear that the nozzle type has a very important and statistically significant (α = 0.05, t-test) influence on the amount of drift for the different ISO nozzle sizes (Figure 5.20). For example, for an ISO 02 nozzle size, the total drift reduction potential (DRP_t) is -136.5% for standard flat fan nozzles, -3.6% for low-drift nozzles and 67.2% for air injection nozzles. Based on *DRP* values, sedimenting drift values at a distance of 2 m of 6.7% for the standard flat fan nozzles, 4.1% for low-drift nozzles and 1.0% for air injection nozzles are calculated for ISO 02 nozzle sizes at standard meteorological conditions (Figure 5.20). These absolute drift values will vary depending on weather conditions as discussed in section 5.3.1. A similar tendency was found for ISO 03 nozzle sizes, with DRP_t values of 0, 38.4 and 89.8%, and for the ISO 04 nozzle sizes, with DRP_t values of 33.9, 54.9 and 77.7%, respectively for the standard flat fan, the low-drift flat fan and the air inclusion nozzles. Hence, there is a very important effect of nozzle type on the *DRP* and DRP_t values. For the same ISO nozzle size and spray pressure, *DRP* and DRP_t values are significantly higher for the air inclusion nozzles followed by the low-drift nozzles and the standard flat fan nozzles but it should be noted that the effect of nozzle type is the most important for smaller nozzle sizes.

For the ISO 02 standard flat fan and low-drift flat fan nozzles, *DRP* values seem to vary depending on the drift distances (Figure 5.18) but because of the high standard deviations for these specific experiments, differences are only statistically significant in two cases (α = 0.05). In those two specific cases, *DRP* values are higher for larger distances and lower for near-field distances. The very important effect of nozzle type on the amount of spray drift is in accordance with the results of several previous studies (Ozkan *et al*., 1997; Derksen *et al*, 1999; Miller, 1999; van de Zande *et al*., 2000 b; Wolf & Frohberg, 2002; Klein & Johnson, 2002).

5.3.2.5. Effect of nozzle size

Total drift reduction potentials (DRP_t) for different nozzle sizes (ISO 02, 03, 04 and 06) and types (standard flat fan nozzles, low-drift flat fan nozzles and air inclusion nozzles) are presented in Figure 5.21 together with the standard deviations. *DRP* values are presented in Figure 5.18 for the different collector distances and a complete overview can be found in Annex 16. The results are based on experiments A to I (Table 5.1) and the reference nozzle is defined as a Hardi ISO F 110 03 standard flat fan nozzle. Based on these *DRP* values and drift equation 5.9 for the reference spraying, expected sedimenting drift curves for these nozzle sizes and types are presented in Figure 5.22 for standard meteorological conditions with a logarithmic scale of the Y-axis.

From these graphs, it is clear that besides the nozzle type, the size of the nozzle is also related to the drift reduction potential. In general, the bigger the ISO nozzle size, the lower the amount of drift (and the higher the *DRP* and DRP_t values) for the same nozzle type and spray pressure.

For the low-drift nozzles, DRP_t values of -3.6, 38.4 and 54.9% were found for ISO 02, 03 and 04 nozzle sizes (Figure 5.21). Because of the relatively high standard deviations and the rather limited number of measurements, the obvious effect of nozzle size cannot be demonstrated statistically at a level of significance of 0.05. Based on *DRP* values, this results in drift values of respectively 1.32, 0.64 and 0.47% at a distance of 5 m for standard weather conditions as presented in Figure 5.22.

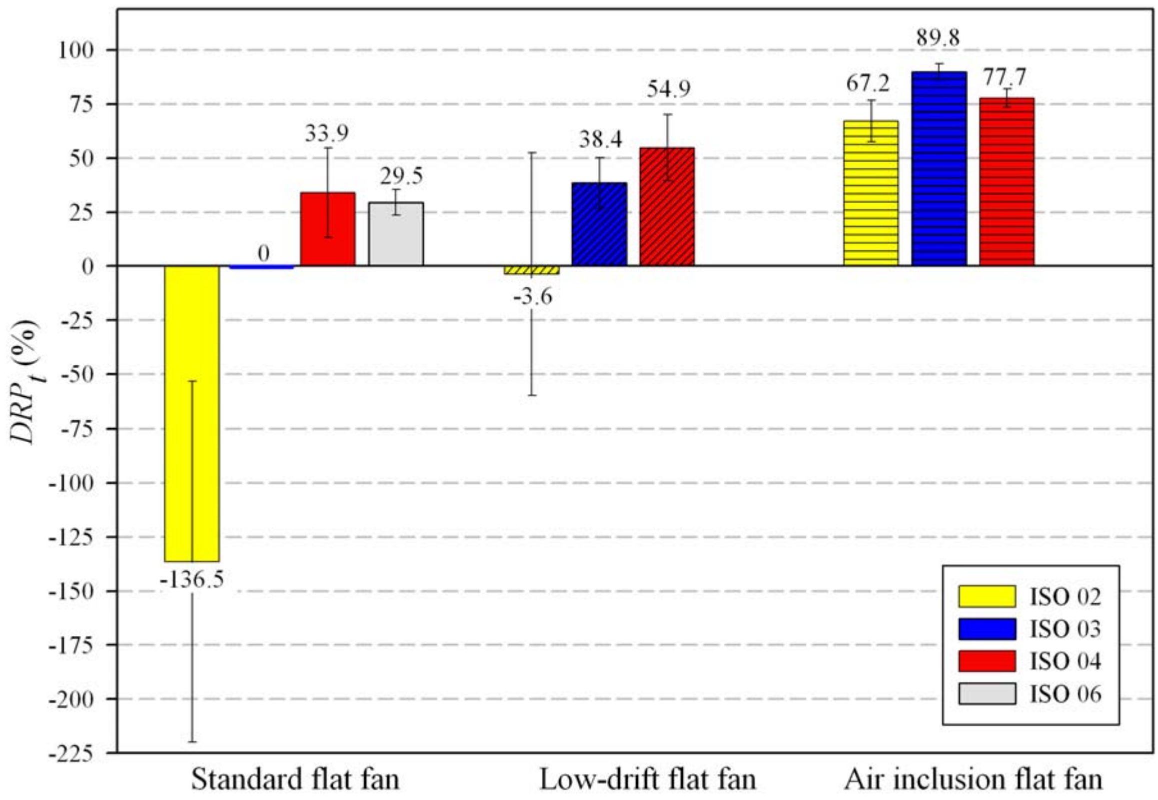

Figure 5.21: *DRP$_t$* values and standard deviations for different Hardi ISO nozzle sizes and types compared to the reference (Hardi ISO F 110 03 standard flat fan) at a spray pressure of 3.0 bar

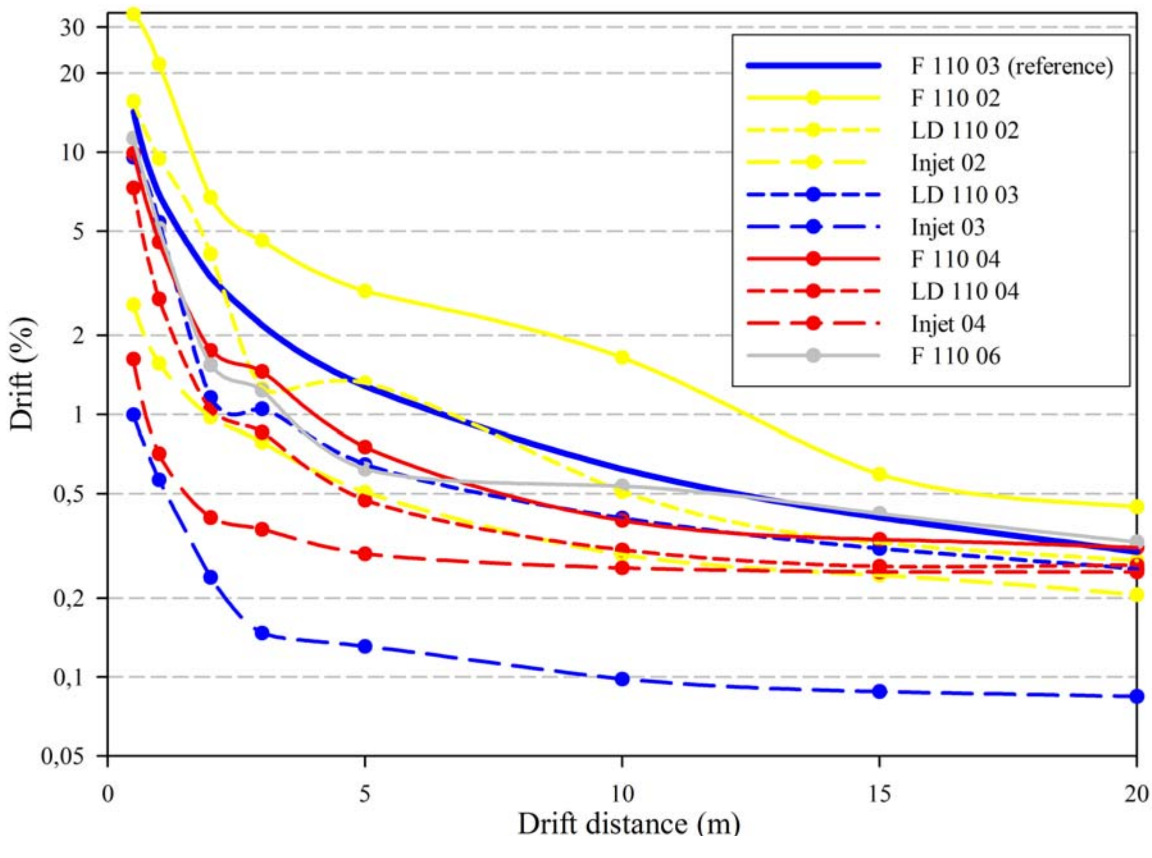

Figure 5.22: Predicted sedimenting drift curves for different Hardi ISO nozzle sizes and types at a spray pressure of 3.0 bar at standard meteorological conditions (*T* = 16°C, $V_{3.25m}$= 3 m.s^{-1} and X_{H_2O}= 8 g.kg^{-1}) with a logarithmic scale of the Y-axis

A similar and statistical significant (α = 0.05) trend was found for the standard flat fan nozzles of ISO sizes 02, 03 and 04 with DRP_t values of respectively, -136.5, 0 and 33.9% (Figure 5.21). For the ISO 06 standard flat fan nozzles (DRP_t = 29.5%), there was only a significant difference with the ISO 02 and ISO 03 standard flat fan nozzles and no significant difference with the ISO 04 standard flat fan nozzles with regard to DRP_t values. For the air inclusion nozzles, the effect of nozzle size on DRP_t values is less clear but DRP_t values are in each case very high (67.2 up to 89.8%) going together with low drift values. At a distance of 3 m, predicted drift values are 0.78, 0.15 and 0.37% respectively for the ISO 02, 03 and 04 air inclusion nozzles. DRP_t values for the ISO 02 air inclusion nozzles (DRP_t = 67.2%) are significantly (α = 0.05) lower than the ISO 03 air inclusion nozzles (DRP_t = 89.8%) which confirms the relation between nozzle size and DRP_t as found for the standard and the low-drift flat fan nozzles. However, also for the ISO 04 air inclusion nozzles (DRP_t = 77.7%), DRP_t values were significantly lower than the ISO 03 air inclusion nozzles and there was no significant difference between the ISO 02 and 04 air inclusion nozzles. Moreover, standard deviations of the results of the air inclusion nozzles are much smaller compared to the other nozzle types.

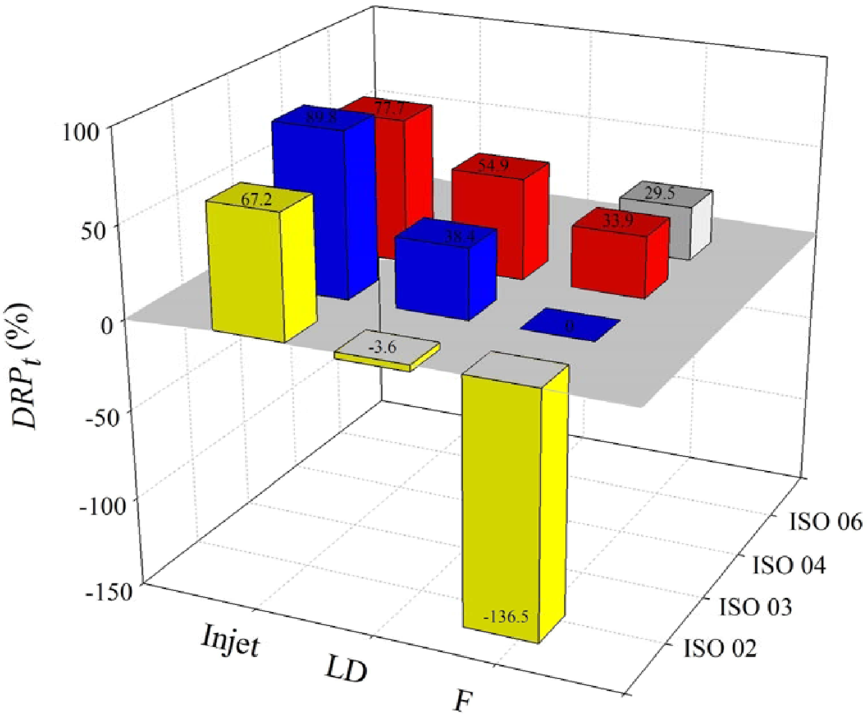

Figure 5.23: *DRP*$_t$ values for different ISO sizes (02, 03, 04 and 06) of Hardi standard flat fan (F), low-drift (LD) and air inclusion nozzles (Injet) at a spray pressure of 3.0 bar

5.3.2.6. Effect of spray pressure

In Figure 5.24, *DRP* values for spray pressures of 2.0, 3.0 and 4.0 bar with the Hardi standard flat fan ISO 03 reference nozzles are presented for different collector distances, as well as the DRP_t and their standard deviations based on experiments J and K (Table 5.1). A complete overview can be found in Annex 16 and reference pressure was defined as 3.0 bar. In Figure 5.25, the corresponding predicted drift curves are presented for standard weather conditions based on *DRP* values and drift prediction equation 5.9 with a logarithmic scale of the X-axis. Same results are presented in Annex 17 with a logarithmic scale of the Y-axis.

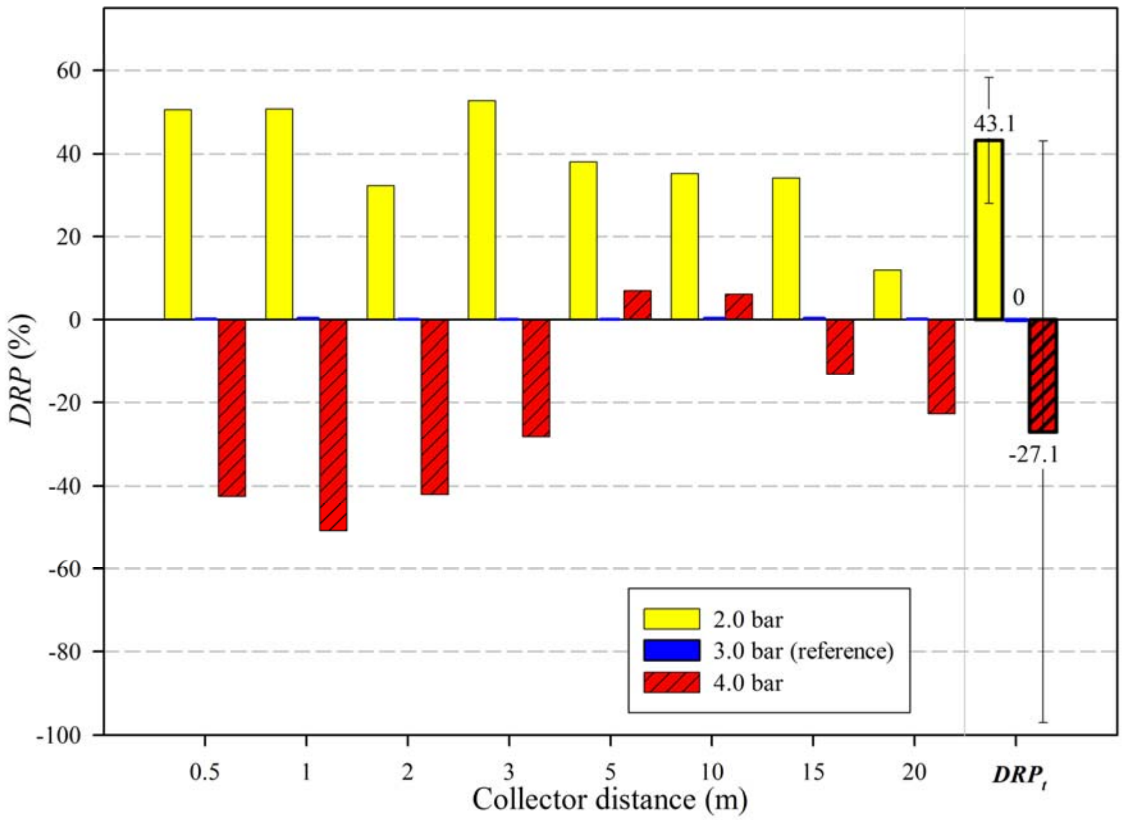

Figure 5.24: *DRP* values at different distances and *DRP$_t$* values (± sd) for Hardi ISO F 110 03 standard flat fan nozzles at spray pressures of 2.0, 3.0 and 4.0 bar

These results show that lowering the pressure from 3.0 to 2.0 bar significantly ($\alpha = 0.05$) decreases the total amount of spray drift with an increase of *DRP$_t$* from 0 to 43.1%. In case of raising the pressure from 3.0 to 4.0 bar, there is a clear tendency that *DRP* and *DRP$_t$* values generally decrease with a *DRP$_t$* value of -27.1% for a pressure of 4.0 bar. However, this tendency cannot be proved statistically at a level of significance of 0.05 because of the large variations in *DRP* and *DRP$_t$* values for the experiments at a pressure of 4.0 bar (experiments K 2-6). These variations in drift values may be due to spray boom movements and variations in wind speed, wind direction and spray line while passing the different sampling transects although this was not observed during the experiments. At distances of 5 and 10 m *DRP* values even increased slightly when pressure was increased but again, differences were not statistically significant ($\alpha = 0.05$). Previous studies carried out by Courshee (1959) and Bode *et al*. (1976) also mentioned that reducing nozzle pressure reduces downwind drift deposits despite the fact that decreasing pressure generally decreases droplet velocities and entrained air velocities. This is caused by an increase in droplet sizes.

Based on *DRP* values, the predicted drift values at a distance of 2 m for spraying pressures of respectively 2.0, 3.0 and 4.0 bar with ISO 03 standard flat fan nozzles, a boom height of 0.50 m and a driving speed of 8 $km.h^{-1}$ for standard weather condition are respectively 2.26, 3.34 and 4.75% (Figure 5.25).

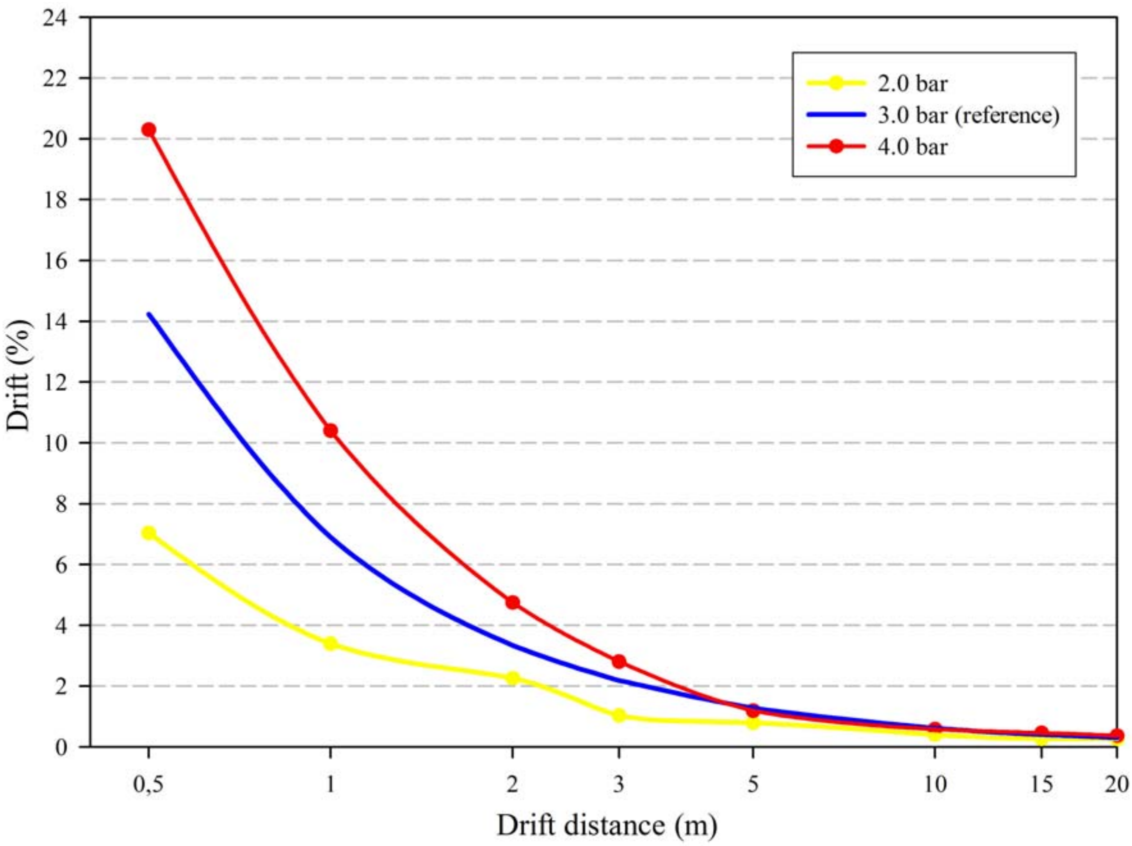

Figure 5.25: Predicted sedimenting drift curves for Hardi ISO F 110 03 standard flat fan nozzles at spray pressures of 2.0, 3.0 and 4.0 bar and standard meteorological conditions (T = 16°C, $V_{3.25m}$ = 3 m.s^{-1} and X_{H_2O}= 8 g.kg^{-1}) with a logarithmic scale of the X-axis

The results from the PDPA laser measurements (Chapter 3) already showed the effect of nozzle type, size and spray pressure on droplet characteristics while the important effect of these characteristics on sedimenting spray drift is demonstrated above. The relation between droplet and drift characteristics will be discussed in detail in Chapter 6.

Comparable studies have been carried out by Taylor *et al*. (1999) van de Zande *et al*. (2000 b) and Balsari *et al*. (2006) calculating the drift reduction potential compared with a reference spraying for different nozzle types, sizes and spray pressures. The results from these studies are presented in Table 5.9.

In general, a good agreement between the different measuring results is found. Differences can be attributed to different reasons i.e.: another definition of reference spraying, differences in crop characteristics (Taylor *et al*., 1989; van de Zande *et al*., 2006), spray pressure, driving speed and nozzles and differences in measuring setup and data analysis. Moreover, the drift reduction classes of the different nozzles, as determined in the Belgian legislation, are presented (Fytoweb, 2007). In 8 out of 10 cases, there is resemblance between results from this study and the Belgian legislation.

Table 5.9: Comparison of drift reduction results of different nozzle-pressure combinations from three other studies and the measuring results from this study

Nozzle type	ISO nozzle size	Drift reduction (%)				
		Results from this study[1]	Taylor *et al.* (1999)[2]	van de Zande *et al.* (2000 b)[3]	Balsari *et al.* (2006)[4]	Fytoweb (2007)[5]
Standard flat fan	02	-136.5		-185		< 50
	03	0	0		0	< 50
	04	33.9		0		< 50
	06	29.5				< 50
Low-drift flat fan	02	-3.6		- 29		< 50
	03	38.4				50-75 %
	04	54.9		72		50-75 %
Air inclusion	02	67.2		78		50-75 %
	03	89.8	88		92	50-75 %
	04	77.7	85	87		75-90 %

Drift reduction classes	25-50 %	50-75 %	75-90 %	> 90 %

[1] Standard flat fan: Hardi ISO F; low-drift flat fan: Hardi ISO LD; air inclusion: Hardi ISO Injet; all measurements at 8 km.h^{-1}, 0.50 m boom height, 3.0 bar pressure

[2] Standard flat fan: Hardi ISO F; air inclusion: Hardi ISO Injet; reference: Hardi ISO F 110 03 at 3 bar; all measurements on short grass with 0.5 m boom height and driving speed of 7.2 km.h^{-1}

[3] Standard flat fan: TeeJet XR; low-drift flat fan: TeeJet DG; air inclusion: Lechler ID; reference: TeeJet XR 110 04 at 3 bar, 0.5 m boom height, 300 L.ha^{-1}; potato crop; drift reduction at 2-3 m from last nozzle

[4] Standard flat fan: TeeJet XR; air inclusion: TeeJet ID; reference: TeeJet XR 110 03 at 5 bar, 0.5 m boom height, 365 L.ha^{-1}; all measurements at 5 bar pressure

[5] Drift reduction class 25-50 % not considered

5.3.2.7. Effect of driving speed

Figure 5.26 presents *DRP* values at different distances for different driving speeds (4, 6 and 10 km.h^{-1}) as well as the DRP_t values and their standard deviations compared to a reference speed of 8 km.h^{-1} based on experiments L, M and N (Table 5.1). A complete overview can be found in Annex 16. The corresponding drift curves for standard weather conditions are represented in Figure 5.27 with a logarithmic scale of the Y-axis and in Annex 17 with a logarithmic scale of the X-axis.

By increasing the driving speed the effective airflow, due to the forward motion of the nozzle, increases and the vertical air jet is bent and distorted. This leads to the escape of the smallest droplets from the spray into the atmosphere downwind of the sprayer resulting in a higher amount of spray drift (Ghosh & Hunt, 1998). This is confirmed by experiments with driving speeds of 4 (DRP_t = 35.3%) and 6 km.h^{-1} (DRP_t = 52.9%) which have significantly higher DRP_t values (α = 0.05) compared with a driving speed of 8 km.h^{-1}. For a speed of 4 km.h^{-1}, *DRP* values are small for small drift distances (0.5 and 1 m) compared to other distances and compared to *DRP* values at a speed of 6 km.h^{-1}. Probably, this can be attributed to spray boom movements or small deviations in spray line or boom height. However, no significant difference in DRP_t values between 4 and 6 km.h^{-1} is found. Similarly, the difference between a speed of 8 km.h^{-1} and 10 km.h^{-1} (DRP_t = 14.6%) is statistically non-significant due to a large variation in *DRP* values between the different repetitions at a speed of 10 km.h^{-1}. This is confirmed by Miller and Smith (1997) who found no significant difference between sprayer speeds of 8 and 12 km.h^{-1}.

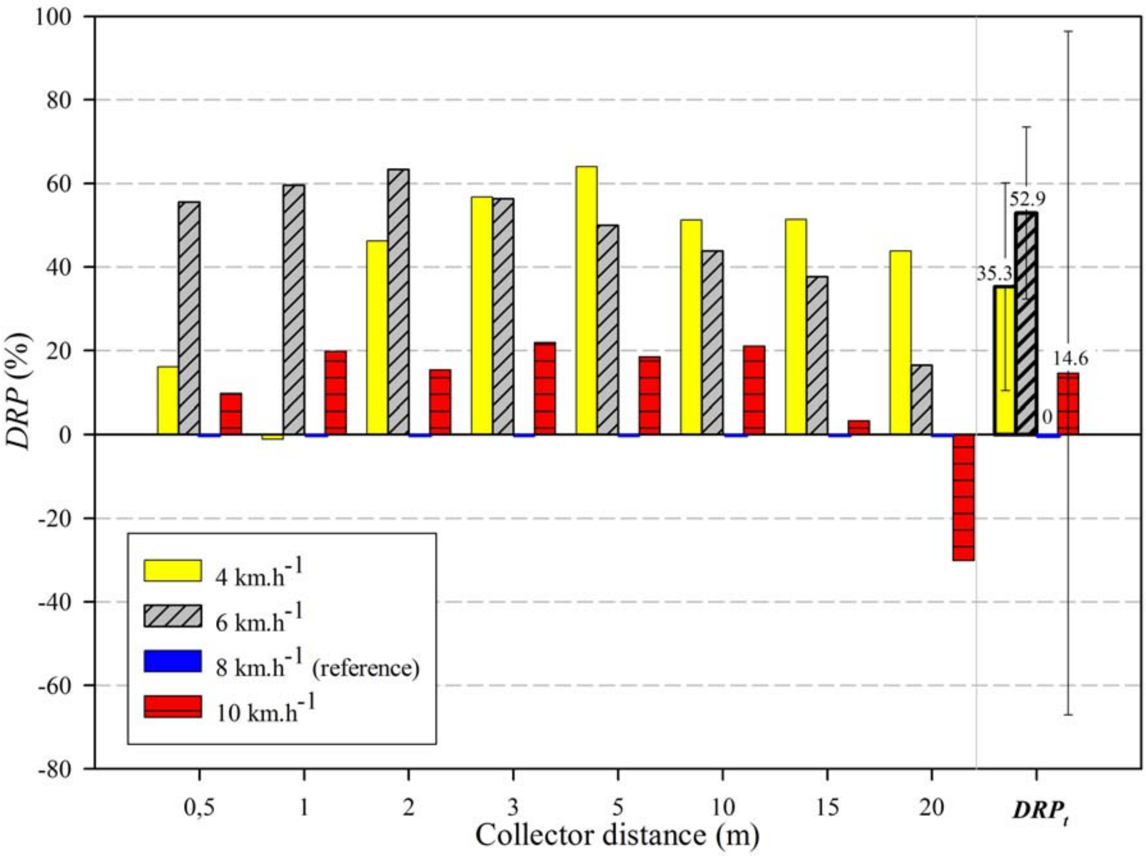

Figure 5.26: *DRP* values at different distances and DRP_t values (± sd) for Hardi ISO F 110 03 standard flat fan nozzles at a spray pressure of 3.0 bar and driving speeds of 4, 6, 8 and 10 km.h^{-1}

Relatively few studies have been carried out on the effect of forward speed on spray drift although tractor and sprayer movement together with its induced air turbulence and boom movement will affect the air circulation. The observed differences in drift values are consistent with previous work which has shown that the penetration of an airflow into a spray structure, and hence drift, is determined by the ratio between the strength of the external airflow and the entrained air velocity within the spray structure. Entrained air velocities are a function of nozzle flow rate which was constant in this study. Miller and Smith (1997) measured an increase in airborne spray drift in the field of approximately 51% for a forward speed increase from 4.0 to 8.0 km.h^{-1} and by 144% when the speed was further increased to 16.0 km.h^{-1}. This corresponds with a drift reduction of 33% when forward speed is decreased from 8 km.h^{-1} to 4 km.h^{-1} which is very comparable with the results from this study (DRP_t = 35.3%).

They also suggest that the largest effects due to sprayer speed are in low wind speed conditions because at higher wind speeds, the wind flow due to the wind alone is sufficient to penetrate the spray structure. In this study, experiments were carried out at different wind speeds. Taylor *et al*. (1989) measured the drift from boom sprayers at forward speeds of 4.0, 7.0 and 10 km.h^{-1} and found an increase in airborne spray drift downwind of approximately 4% as speed increased from 4.0 to 7.0 km.h^{-1} and 90% for a speed increase from 7.0 to 10.0 km.h^{-1}. Van de Zande *et al.* (2005 a) measured an increase in spray drift from 29 up to 51% when driving speed increased from 6 to 12 km.h^{-1} using conventional XR 110 04 nozzles.

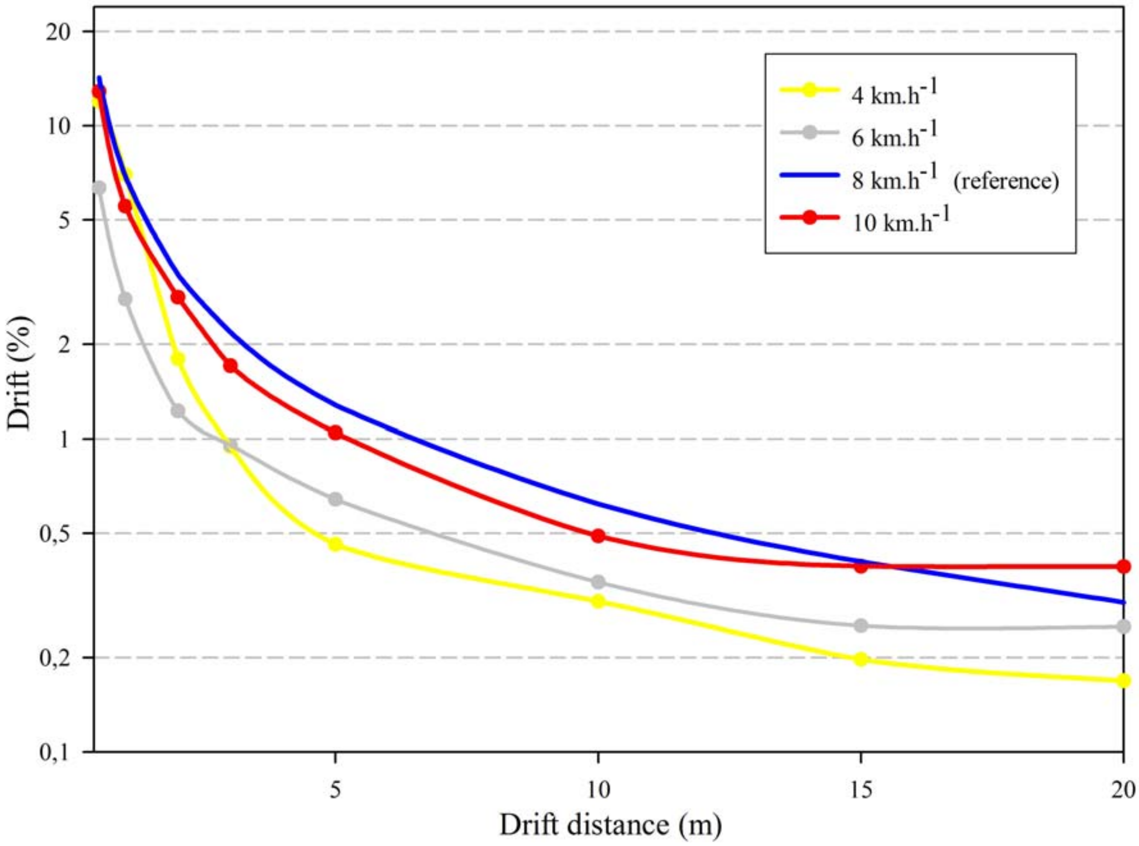

Figure 5.27: Predicted sedimenting drift curves for Hardi ISO F 110 03 standard flat fan nozzles at a spray pressure of 3.0 bar and standard meteorological conditions (T = 16°C, $V_{3.25m}$= 3 m.s^{-1} and X_{H_2O}= 8 g.kg^{-1}) for driving speeds of 4, 6, 8 and 10 km.h^{-1} with a logarithmic scale of the Y-axis

5.3.2.8. Effect of spray boom height

Figure 5.28 presents *DRP* values for different boom heights (0.30, 0.50 and 0.75 m) and collector distances as well as DRP_t values together with their standard deviations based on experiments O and P (Table 5.1). These results are also presented in Annex 16. Experiments were carried out with Hardi ISO F 110 03 standard flat fan nozzles at a pressure of 3.0 bar and a driving speed of 8 km.h^{-1}. Reference boom height was defined as 0.50 m. In Figure 5.29, the corresponding predicted drift curves are presented for standard weather conditions based on *DRP* values and drift prediction equation 5.9 with a logarithmic scale of the X-axis. The same results are presented in Annex 17 with a logarithmic scale of the Y-axis.

From these results, the effect of boom height on spray drift is very clear. Lowering the spray boom height from 0.50 m to 0.30 m, significantly ($\alpha = 0.05$) decreases the amount of spray drift (DRP_t = 40.1%). Opposite results were found when raising the spray boom up to 0.75 m resulting in a DRP_t of -49.9%. In both cases, *DRP* values are almost constant for the different distances despite the relatively large variations in *DRP* values between the different repetitions. This important effect of boom height on sedimenting spray drift can be explained by the fact that when the distance between the spray nozzle and the target area increases, the impact of wind velocity and therefore drift increases too. Moreover, wind speed increases with height. With lower boom heights, the initial droplet speed may be large enough for the droplet to reach its target before drift occurs but adequate boom stabilisation is necessary to maintain an even spray pattern.

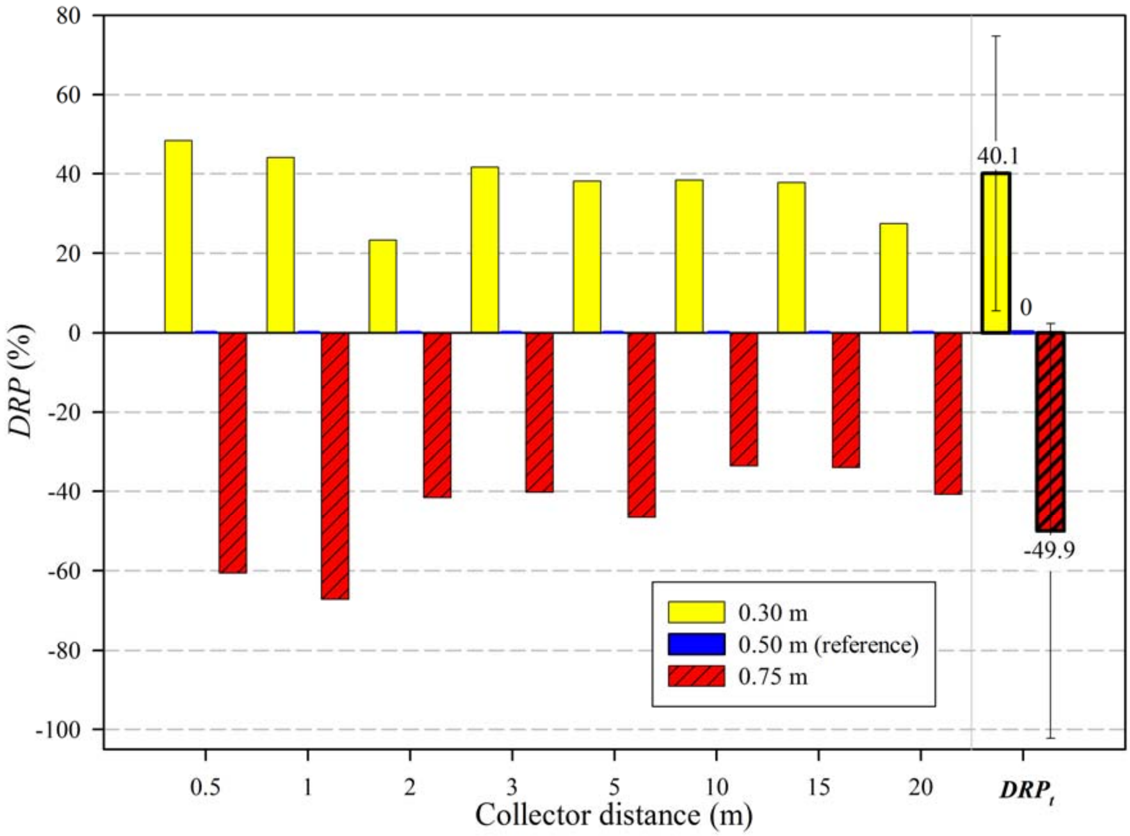

Figure 5.28: *DRP* values at different distances and DRP_t values (± sd) for Hardi ISO F 110 03 standard flat fan nozzles at a spray pressure of 3.0 bar, a driving speed of 8 km.h^{-1} and for boom heights of 0.30, 0.50 and 0.75 m

Based on *DRP* values, predicted drift values are 0.38, 0.62 and 0.83% at a distance of 10 m for boom heights of respectively 0.30, 0.50 and 0.75 m with ISO 03 standard flat fan nozzles, a spray pressure of 3.0 bar and a driving speed of 8 km.h^{-1} for standard weather conditions (Figure 5.29).

Other researchers also concluded that operating at a spray boom height as close as possible to the vegetation, without sacrificing the uniformity of the spray pattern, is a good way to reduce drift (Göhlich, 1983; Combellack *et al*., 1996; Mueller & Womac, 1997; Ozkan, 1998; Teske & Thistle, 1999; de Jong *et al*., 2000, Stallinga *et al*., 2004). De Jong measured sedimenting drift reduction percentages from -62 up to -116% when boom height was increased from 0.50 m to 0.70 m and from 56 up to 58% when boom height was decreased from 0.50 to 0.30 m. Balsari *et al*. (2006) found a drift reduction percentage of -35% when boom height was increased from 0.50 to 0.80 m. For similar variations in boom height, DRP_t values of 40.1% and -49.9% were found, respectively, when lowering and raising boom height. These figures are confirmed by the drift model developed by Holterman and van de Zande (1996) and Holterman *et al*. (1997). It is important to maintain an even spray pattern when lowering the spray boom by choosing the correct nozzle spacing and spray angle with a sprayer equipped with an adequate boom stabilisation.

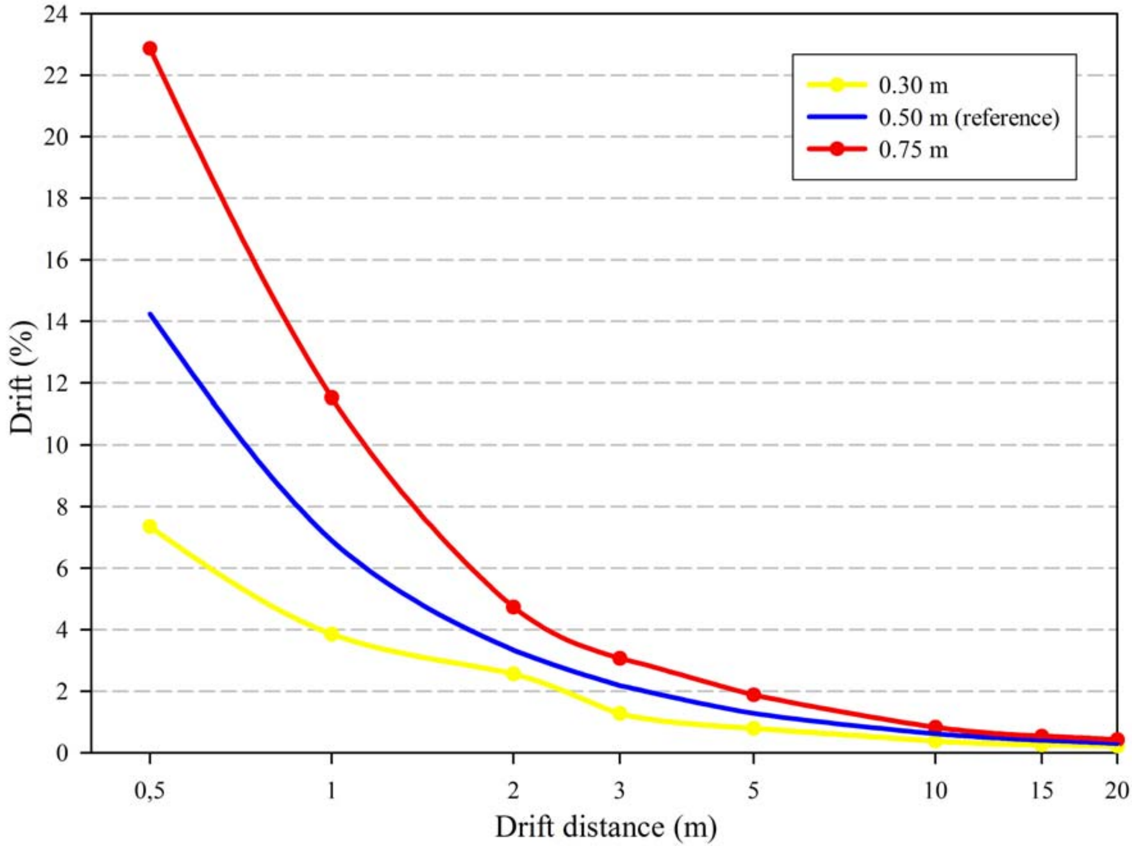

Figure 5.29: Predicted sedimenting drift curves for Hardi ISO F 110 03 standard flat fan nozzles at a spray pressure of 3.0 bar and a driving speed of 8 km.h^{-1} at standard meteorological conditions (T = 16°C, $V_{3.25m}$= 3 m.s^{-1} and X_{H_2O}= 8 g.kg^{-1}) for boom heights of 0.30, 0.50 and 0.75 m with a logarithmic scale of the X-axis

5.3.2.9. Effect of air assistance

As described in detail in section 2.2.2.3, an air assistance system is a system capable of supplying airflows to carry and disperse sprays formed by atomizers. This might lead to a drift reduction (Young, 1991; van de Zande *et al*. 2000 a) as well as an increased deposition towards the target. In this research, the Hardi Twin Force system was evaluated, a system where atomizers are outside the air stream but are directed into the stream at a specific angle.

In order to quantify the effect of the Hardi Twin air assistance system on spray drift, 16 experiments with air assistance in combination with Hardi ISO F 110 02, F 110 03, LD 110 02, LD 110 03 were carried out (Table 5.1, experiments Q up to T). All sprayings were carried out at a driving speed of 8 km.h^{-1}, a spray pressure of 3.0 bar and with a boom height of 0.50 m with an optimal air volume which was determined visually for the actual meteorological conditions. Air volumes varied from 30 to 50% of the maximum capacity which is 2000 m^3.h^{-1} for each meter of spray boom. During the experiments, the liquid flow was directed directly towards the ground (release angle of 0°) which involves an air jet orientation of 15° forward. *DRP* values for different distances and DRP_t values with their standard deviations for these nozzles with air assistance are presented in Figure 5.30 with the reference spraying set as 0%. A complete overview of *DRP* and DRP_t values and their standard deviations is presented in Annex 16. In Figure 5.31, DRP_t values are presented for the same nozzle types with and without air assistance.

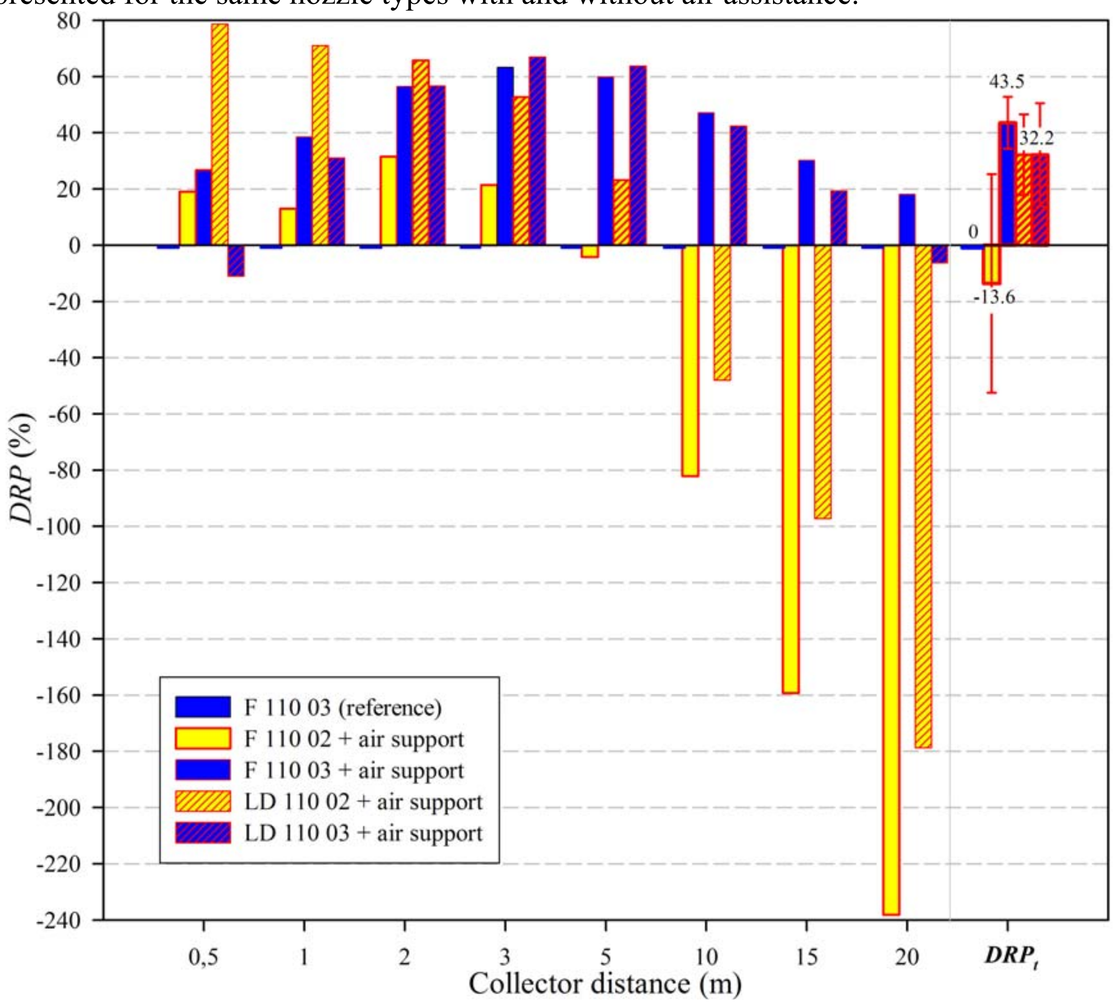

Figure 5.30: ***DRP*** **values at different distances and** DRP_t **values (± sd) for Hardi ISO F 110 02 and F 110 03 standard flat fan nozzles and Hardi ISO LD 110 02 and LD 110 03 low-drift flat fan nozzles with air assistance at a pressure of 3.0 bar, a driving speed of 8 km.h^{-1} and a boom height of 0.50 m**

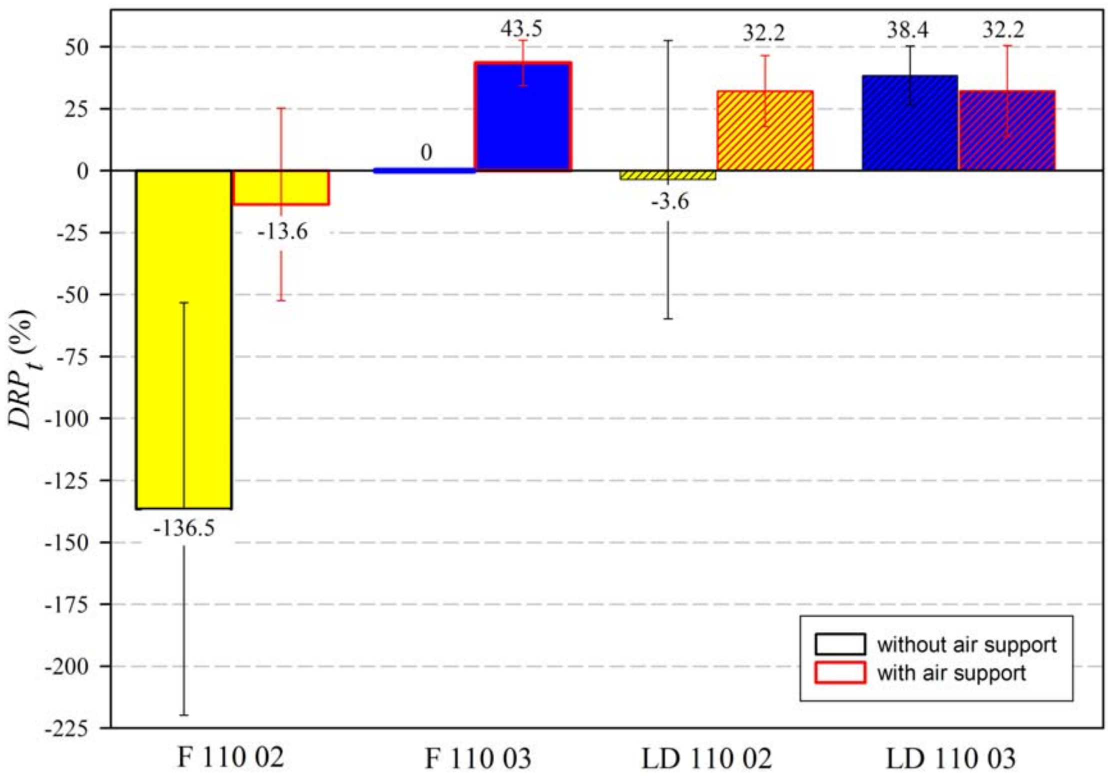

Figure 5.31: *DRP_t* values and standard deviations for Hardi ISO F 110 02, F 110 03, LD 110 02 and LD 110 03 nozzles with and without air assistance

Based on DRP_t values of the four nozzle types with and without air assistance, drift reduction factors α_d can be calculated expressing the difference between spraying with and without air assistance for the different nozzle types, using the following formula:

$$\alpha_d = \frac{(1 - \frac{DRP^B}{100})}{(1 - \frac{DRP^A}{100})} \qquad (5.11)$$

With

α_d – drift reduction factor expressing the ratio between the amount of spray drift without air assistance and with air assistance with the same nozzle type,

DRP^B – drift reduction potential for a specific application technique without air assistance (%),

DRP^A – drift reduction potential for the same application technique but with the use of air assistance (%).

The results are presented in Table 5.10. Of course, this formula can also be used to compare different other spray application techniques. Based on the *DRP* values and drift equation 5.9 for the reference spraying, expected sedimenting drift curves are presented in Figure 5.32 for the Hardi ISO F 110 02, F 110 03, LD 110 02, LD 110 03 nozzles with and without air assistance at standard meteorological conditions (T = 16°C, $V_{3.25m}$= 3 m.s^{-1} and X_{H_2O}= 8 g.kg^{-1}) with a logarithmic scale of the X-axis. Same results are presented in Annex 14 with a logarithmic scale of the Y-axis.

Table 5.10: Drift reduction factors α_d, DRP_t and $D_{v0.5}$ for spraying with and without air assistance for Hardi ISO F 110 02, F 110 03, LD 110 02 and LD 110 03 nozzles

Experiment	Nozzle type	Air assistance	DRP_t (%)	α_d	$D_{v0.5}$ (μm)
A	F 110 02	no	-136.5	2.08	214.2
Q		yes	-13.6		
RS	F 110 03	no	0	1.77	273.6
R		yes	43.5		
B	LD 110 02	no	-3.6	1.53	294.9
S		yes	32.2		
D	LD 110 03	no	38.4	0.91	348.2
T		yes	32.2		

F, Hardi ISO 110 standard flat fan nozzles; LD, Hardi ISO 110 low-drift nozzles; DRP_t, total drift reduction potential; α_d, drift reduction factor; $D_{v0.5}$, diameter below which smaller droplets constitute 50% of the total volume

It is clear that the use of air assistance has an important effect on the total amount of drift for the Hardi ISO F 110 02, F 110 03 and LD 110 02 nozzles. For these nozzles, the use of air assistance resulted in an increase in DRP_t values from -136.5% to -13.6%, from 0 to 43.5% and from -3.6 to 32.2% (Table 5.10). This increase was not statistically significant (α = 0.05) for the LD 110 02 nozzles, because of the relatively high standard deviations and the rather limited number of measurements for the LD 110 02 nozzles without air assistance as already mentioned in section 5.3.2.4. These increases in DRP_t values correspond with drift reduction factors α_d of, respectively, 2.08, 1.77 and 1.53. Hence, the highest drift reduction factor is found for the F 110 02 nozzles despite the negative DRP_t values. This means that for the F 110 02 nozzles, the amount of spray drift is strongly reduced with a factor of 2.08 using air assistance but still higher than the reference spraying (DRP_t = -13.6%). For the F 110 03 reference nozzles, Taylor *et al*. (1999) measured a drift reduction of 45% using air assistance which is comparable with the result from this study (DRP_t = 43.5%).

Remarkably, for the LD 110 03 nozzles, the use of air assistance had no significant effect on the total amount of spray drift with a DRP_t value of 38.4% without air assistance and 32.2% with air assistance resulting in an α_d factor of 0.91. This is partly caused by the very low *DRP* values for the LD 110 03 nozzles at small distance (0.5 and 1 m) which might be attributed to deviations in driving direction or a bad setup of the air assistance system although standard deviations are relatively small.

Also for the other nozzle types, an important effect of drift distance on *DRP* values is observed as presented in Figure 5.30. *DRP* values generally decrease with increasing drift distance especially for the F 110 02 and LD 110 02 nozzles. For example for the LD 110 02 nozzles with air assistance, *DRP* values are 78.6, 71.0, 65.7, 52.7, 23.1, -48.0, -97.2 and -178.7%, respectively, for drift distances of 0.5, 1, 2, 3, 5, 10, 15 and 20 m. This means that the sedimenting drift profile is flatter compared with the drift profile of the reference spraying. For the F 110 02 and LD 110 02 nozzles, the use of air assistance even increased drift values at high distances. Comparable results were found by Cooke *et al*. (1990) and Hislop *et al*. (1993). Both found that the air-assisted sprayer produced more drift when compared to standard sprayers under certain conditions. From these results, it can be concluded that parameters such as air speed and direction need to be optimized depending on wind and crop conditions to optimize drift reduction.

Based on *DRP* values and equation 5.9, predicted drift values at standard meteorological conditions are 1.33, 0.51, 0.99 and 0.46% at a distance of 5 m, respectively, for F 110 02, F 110 03, LD 110 02 and LD 110 03 nozzles with the use of air assistance and 2.95, 1.28, 1.32 and 0.64% for the same nozzle types without the use of air assistance (Figure 5.32).

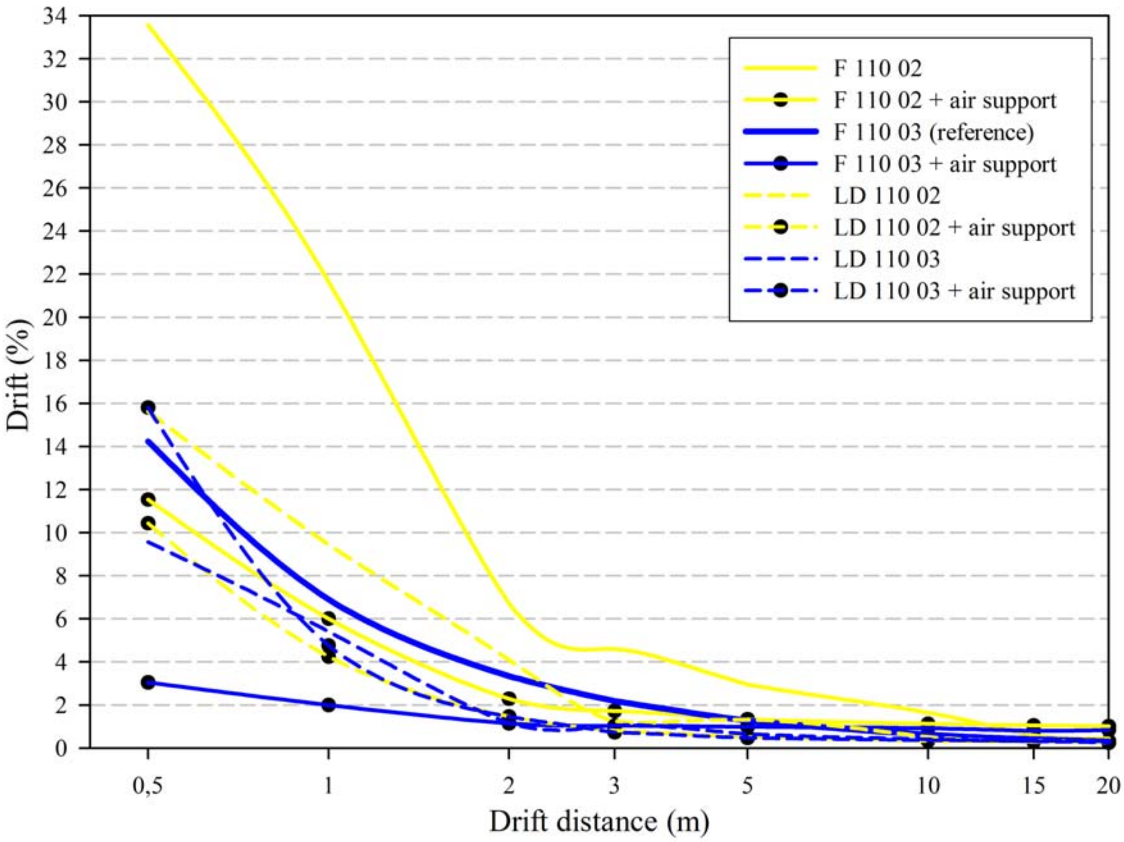

Figure 5.32: Predicted sedimenting drift curves for Hardi ISO F 110 02 and F 110 03 standard flat fan nozzles and Hardi ISO LD 110 02 and 110 03 low-drift flat fan nozzles with and without air assistance at a spray pressure of 3.0 bar, a boom height of 0.50 m and a driving speed 8 km.h^{-1} at standard meteorological conditions (T = 16°C, $V_{3.25m}$= 3 m.s^{-1} and X_{H_2O}= 8 g.kg^{-1}) with a logarithmic scale of the X-axis

Based on these results and the results from the droplet characterisation discussed in Chapter 3, it is clear that the drift reduction factor α_d, expressing the ratio between the amount of spray drift without air assistance and with air assistance, is linked with the droplet size characteristics (e.g. $D_{v0.5}$) of the spray as presented in Table 5.10. An R^2 of 0.95 is found between α_d and $D_{v0.5}$ values. Relationships between droplet and drift characteristics are discussed in more detail in Chapter 6. Hence, the use of air assistance has the highest impact on the amount of spray drift for the finer sprays which was also reported by Young (1991) and Howard and Mulrooney (1995).

The observed drift reduction potentials are generally lower than the ones found in literature mainly because the experiments were carried out on a flat mowed meadow which is different from a developed crop. Taylor *et al.* (1989) and Hagenvall and

Arvidsson (1995) also found drift reduction percentages of about 50% when using air assistance over a stubble and of about 80% when spraying a developed crop. Van de Zande (2002) found drift reduction factors of 4.54 and 2.63, respectively, for ISO 02 standard flat fan nozzles and ISO 02 low-drift nozzles when spraying potatoes based on results presented in Table 2.6. Hence, drift reduction percentages are expected to be higher when spraying a developed crop. Based on previous studies (Taylor *et al*., 1989; May, 1991; Pompe & Holterman, 1992) it might also be assumed that emissions to the ground would also have been lower when air and spray were released with a forward angle instead of directly towards the ground.

To finalize this chapter, an overview of the DRP_t values for the 21 different spray application techniques (RS, A-T, Table 5.1) investigated in this study are presented in Figure 5.33 and the corresponding predicted drift curves at standard meteorological conditions in Annex 18. From these graphs and the discussion above, it is clear that the spray application technique has a very important effect on drift characteristics and that different spray application techniques can be ranked according to their drift reduction potential. The highest drift values were found using a fine ISO 02 standard flat fan nozzle at a spray pressure of 3.0 bar (DRP_t= -136.5%), the lowest drift values spraying with ISO 03 air inclusion nozzles also at a spraying pressure of 3.0 bar (DRP_t= 89.8%). In this study, only drift of pesticides was considered, but it is important to keep in mind that a drift reduction technique can possibly lead to an increased soil deposition underneath the crop canopy and, therefore, increases the risk of water contamination due to leaching from the soil.

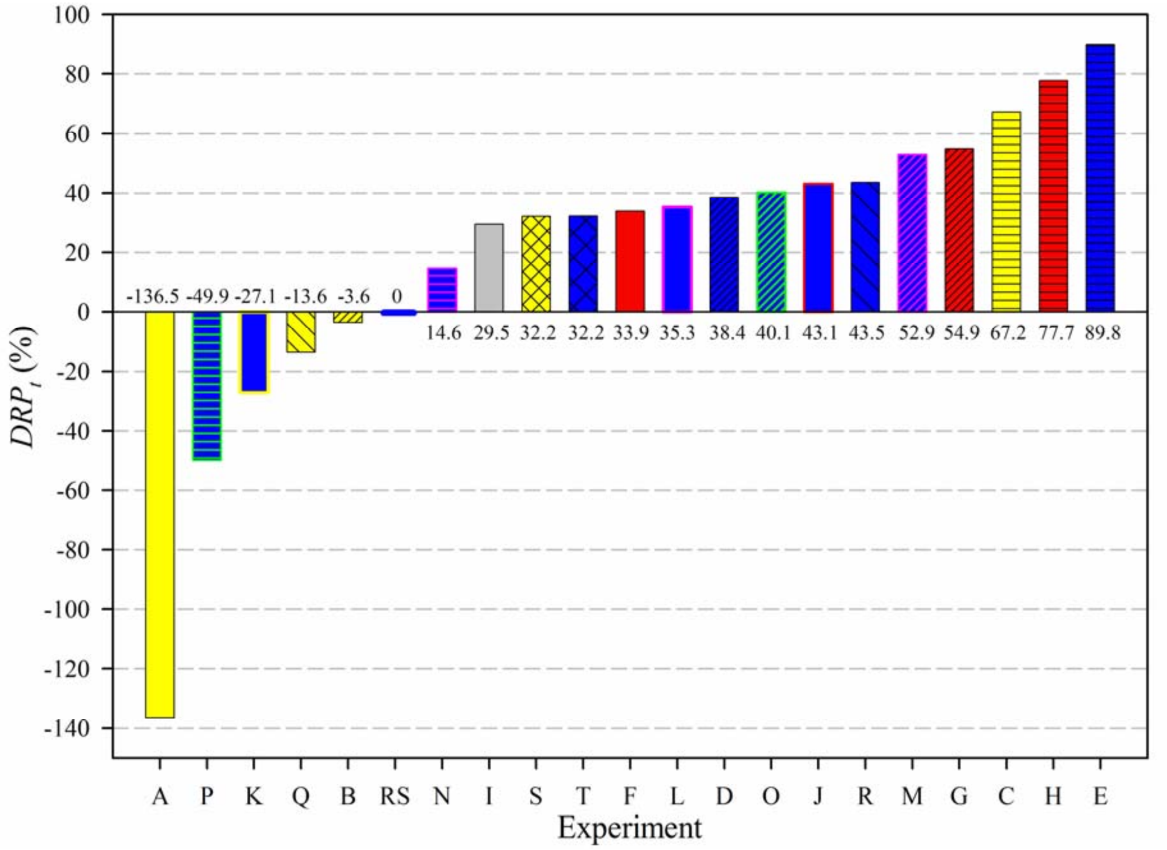

Figure 5.33: *DRP_t* values for the different spray application techniques investigated in this study (RS, A-T) described in Table 5.1

5.3.3. Comparison with results from other studies

Although it is difficult to compare different drift studies due to an inability to isolate and correct for weather differences (Bird *et al.*, 1996) and variations in spray application techniques, crop conditions and methodologies, a comparison of the results from this study with different other studies was done. Figure 5.34 presents the sedimenting drift curves resulting from this study using the Hardi Injet 03, F 110 02 and F 110 03 nozzles at standard meteorological conditions, a spray pressure of 3.0 bar, a boom height of 0.50 m and a driving speed of 8 km.h^{-1} together with drift data from different other studies (Ganzelmeier *et al.*, 1995; Arvidsson, 1997; SDTF, 1997; Gilbert, 2000; BBA, 2000 b; van de Zande *et al.*, 2002 a) both with logarithmic axes. Remember that the lowest DRP_t value in this study was found for the F 110 02 nozzles and the highest DRP_t value for the Injet 03 nozzles. Drift curves from the different other spray application techniques investigated in this study are situated between those outer curves. Moreover, results from the reference spraying are presented.

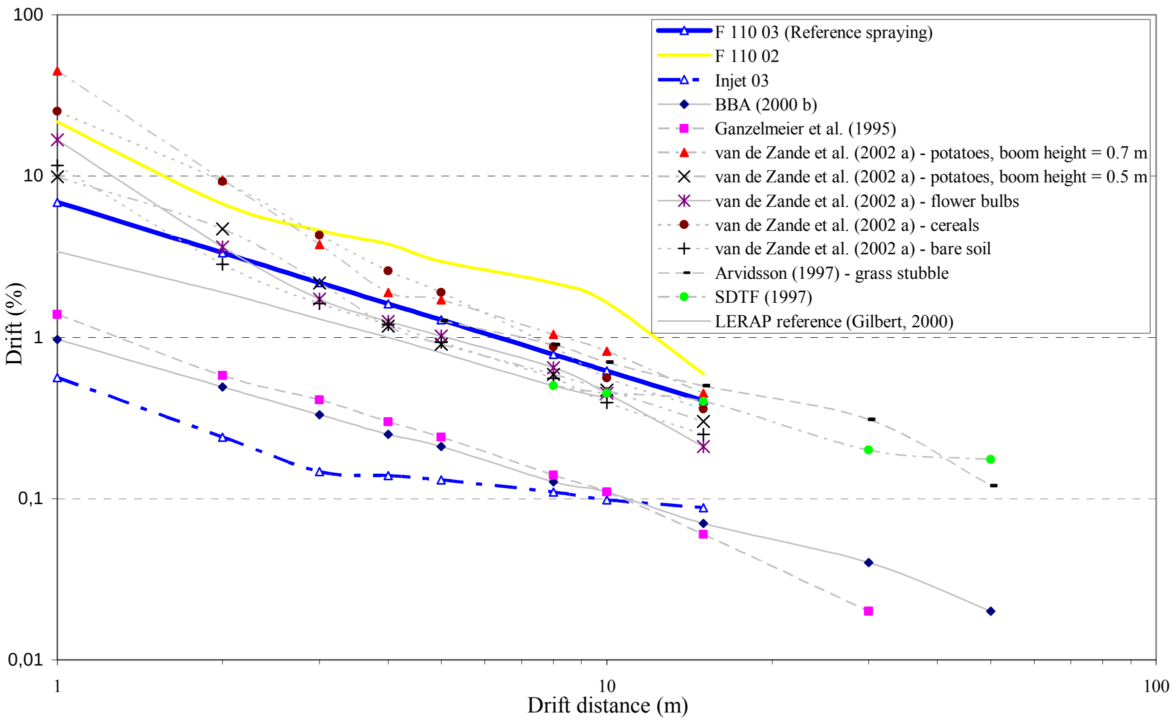

Figure 5.34: Sedimenting drift curves for Hardi ISO F 110 02, F 110 03 (reference spraying) and Injet 03 nozzles at a spray pressure of 3.0 bar, a boom height of 0.50 m and a driving speed of 8 km.h^{-1} at standard meteorological conditions (T = 16°C, $V_{3.25m}$= 3 m.s^{-1} and X_{H_2O}= 8 g.kg^{-1}) together with drift data from different other studies

As already mentioned in section 1.4, drift curves from the different studies can differ by as much as a factor of ten. The results from the reference spraying are in the same range of magnitude as the results from Arvidsson (1997), SDTF (1997), Gilbert (2000) and van de Zande *et al.* (2002 a). Again, deviations can be attributed to differences in spray application technique, crop and weather conditions and methodology. Drift results from the F 110 02 nozzle are situated in the higher region of this graph and are within the same range as the results from van de Zande *et al.* (2002 a) in potatoes with a boom height of 0.70 m and in cereals. Mainly for the higher drift distances, the highest drift results were found for the F 110 02 nozzles in comparison with the other studies. This is logical, because from all the application techniques tested in this study, the F 110 02 nozzles were found to give the highest drift values.

From Figure 5.34, it is clear that German drift values (Ganzelmeier *et al*., 1995; BBA, 2000 b) are much lower than the results of the different other studies and the results of the reference spraying. German drift values and the reference drift curve from this study have the same downward trend but absolute results differ by a factor of 5 to 6. This is important to consider because German drift values are still used in the registration procedure of plant protection products in Belgium. This difference can (partly) be explained by the fact that 19 out of the 50 German experiments were based on measurements with low-drift nozzles and moreover, the 90% percentiles of the drift values were used. That is why results of other researches and of the reference spraying, which were performed with a medium spray quality nozzle, reflect higher spray depositions as already concluded by van de Zande *et al*. (2002 a) and Carlsen *et al*. (2006 b). For the spray application techniques considered in this thesis, the lowest drift results were found for the Hardi ISO Injet 03 air inclusion nozzles. This drift curve is even below the German drift curves.

5.4. Conclusions

A reliable and feasible spray drift measurement protocol for boom sprayers has been set-up according to ISO 22 886 and 108 drift experiments were successfully carried out on grassland under different weather conditions with different spray application techniques. Sedimenting spray drift was determined by sampling in a defined downwind area at 24 different positions using horizontal drift collectors (Machery-Nachel filter paper) in combination with a fluorescent tracer brilliant sulfoflavine (BSF) with drift measurements up to 20 m from the directly sprayed zone. Meteorological conditions were continuously monitored during each drift experiment.

Based on 27 drift experiments with the reference spraying (RS 1-27) under a wide range of atmospheric conditions, a non-linear drift prediction equation was set up to predict the expected magnitude of sedimenting drift for various drift distances and atmospheric conditions for the reference spray application technique on grassland. This reference spraying is defined as a standard horizontal spray boom without air assistance, a boom height of 0.50 m, a nozzle distance of 0.50 m, ISO 110 03 standard flat fan nozzles at 3 bar (1.2 $L.min^{-1}$) and a driving speed of 8 $km.h^{-1}$, resulting in an application rate of approximately 180 $L.ha^{-1}$.

The drift prediction equation is composed of four independent, non-correlated variables namely: drift distance, average wind speed at a height of 3.25 m, average temperature and absolute humidity. These measurements proved the importance of weather conditions (temperature, humidity and wind speed) on the amount of sedimenting spray drift. Decreasing wind speed and temperature and increasing absolute humidity decreases the amount of sedimenting spray drift. In the normal range of weather conditions, the effect of air humidity and temperature is more important than the effect of wind velocity because of the effect of evaporation which reduces droplet sizes. The drift prediction equation was validated successfully based on 5 reference sprayings. This equation can be used to quantify the effect of meteorological conditions on the amount of spray drift, to compare measurements using other spraying techniques under different weather conditions to the reference spraying and to perform spray drift risk assessments.

Moreover, 76 drift experiments were carried out to measure sedimenting drift percentages of 20 other spray application techniques. Drift results of the different other sprayings are compared with the reference spraying by calculating their drift reduction potential (DRP_t) which expresses the percentage of drift reduction. These percentages were calculated by comparing the measured drift values of the other spray application techniques with the predicted drift values of the reference spraying (using the drift prediction equation) for the same weather conditions.

Drift experiments were performed for several combinations of nozzle type (flat fan, low-drift, air inclusion) and size (ISO 02, 03, 04 and 06), spray pressure (2.0, 3.0 and 4.0 bar), driving speed (4, 6, 8 and 10 km.h^{-1}), spray boom height (0.3, 0.5 and 0.75 m) and air assistance. Nozzle type as well as spray pressure, driving speed, spray boom height and air assistance have an important effect on the amount of spray drift with total drift reduction potentials varying from -136.5 up to 89.8%.

Air inclusion nozzles have the highest drift reduction potential followed by the low-drift nozzles and the standard flat fan nozzles and the effect on drift deposits is high. Moreover, the effect of nozzle type is most important for smaller nozzle sizes. DRP_t values varied from -136.5, -3.6 and 67.2% for the ISO 02 nozzle sizes, respectively, for the standard, the low-drift and the air inclusion flat fan nozzles. For the same nozzle types, DRP_t values were 0, 38.4 and 89.8% for the ISO 03 nozzles sizes and 33.9, 54.9 and 77.7% for the ISO 04 nozzle sizes. For the same nozzle type and pressure, bigger ISO nozzle sizes correspond with lower amounts of spray drift especially for the standard and the low-drift flat fan nozzles. Investigating the effect of spray pressure for the standard ISO 03 flat fan nozzles, raising the spray pressure increased the amounts of spray drift. DRP_t values were -27.1% for a pressure of 4.0 bar and 43.1% for a pressure of 2.0 bar.
It is clear that the effect of nozzle type, size and spray pressure on spray drift are related with the droplet characteristics of the sprays. The relation between droplet and drift characteristics will be discussed in detail in Chapter 6.

Besides nozzle type, size and spray pressure, all having an effect on spray quality, driving speed and spray boom height also influence the amount of sedimenting spray drift. In general, a decrease in spray drift was observed for lower driving speeds with DRP_t values of 35.3 and 52.9% for driving speeds of 4 and 6 km.h^{-1}. The difference in drift values between the reference speed of 8 km.h^{-1} and a speed of 10 km.h^{-1} was statistically non-significant. By increasing the driving speed the effective airflow, due to the forward motion of the nozzle, increases and the vertical air jet is bent and distorted. This leads to the escape of the smallest droplets from the spray into the atmosphere downwind of the sprayer resulting in a higher amount of spray drift (Ghosh & Hunt, 1998). This is confirmed by experiments with driving speeds of 4 (DRP_t = 35.3%) and 6 km.h^{-1} (DRP_t = 52.9%) which have significantly higher DRP_t values ($\alpha = 0.05$) compared with a driving speed of 8 km.h^{-1}. For a speed of 4 km.h^{-1}, *DRP* values are small for small drift distances (0.5 and 1 m) compared to other distances and compared to *DRP* values at a speed of 6 km.h^{-1}. Probably, this can be attributed to spray boom movements or small deviations in spray line or boom height. However, there is no significant difference in DRP_t values between 4 and 6 km.h^{-1}. Similarly, the difference between a speed of 8 km.h^{-1} and 10 km.h^{-1} (DRP_t = 14.6%) is statistically non-significant due to a large variation in *DRP* values between the different repetitions at a speed of 10 km.h^{-1}. This is confirmed by Miller and Smith (1997) who found no significant difference between sprayer speeds of 8 and 12 km.h^{-1}.

It was found that operating at a spray boom height as close as possible to the vegetation, without sacrificing the uniformity of the spray pattern, is a good way to reduce drift. Lowering the spray boom height from 0.50 m to 0.30 m decreased the amount of spray drift (DRP_t = 40.1%). Opposite results were found when raising the spray boom up to 0.75 m resulting in a DRP_t of -49.9%.

Finally, the effect of air assistance was evaluated for four different nozzle types (Hardi ISO F 110 02, F 110 03, LD 110 02, LD 110 03). A reducing effect on the total amount of spray drift was demonstrated for the Hardi ISO F 110 02, F 110 03 and LD 110 02 nozzles with drift reduction factors α_d of, respectively, 2.08, 1.77 and 1.53. The use of air assistance had no significant effect for the LD 110 03 nozzles on the total amount of spray drift. Hence, the use of air assistance has the highest impact on the amount of spray drift for the finer sprays.

In conclusion, spray drift is affected by the spray application technique as well as the weather conditions and it is important to bring into account variations in meteorological conditions when comparing different drift experiments. A large database with (absolute) near-field drift results is made available to enlarge the international drift database with information about the effects of climatological conditions for different spray application techniques. The results from these field drift measurements are also used to validate a computational fluid dynamics drift-prediction model (Baetens *et al*., 2006; 2007 a) and are generally in good agreement with the results from different other studies although drift studies are difficult to compare due to differences in weather conditions, spray application techniques, methodologies and crop conditions.

Chapter 6 **Comparison between indirect and direct drift assessment means**

6.1. Introduction

In this study, different spray application techniques have been tested with three different drift assessment means which are PDPA laser measurements, wind tunnel measurements and field drift measurements. An overview is presented in Table 6.1.

Table 6.1: Overview of the tested spray application techniques with the PDPA laser (Chapter 3), in the wind tunnel (Chapter 4) and in the field (Chapter 5)

PDPA laser			Wind tunnel				Field conditions					
Nozzle Type	ISO nozzle size	Pressure (bar)	Nozzle Type	ISO nozzle size	Pressure (bar)	Nozzle height (m)	Nozzle Type	ISO nozzle size	Pressure (bar)	Boom height (m)	Speed (km.h^{-1})	Air assistance
F	02	3.0	F	02	3.0	0.50	F	02	3.0	0.50	8	no
							F	02	3.0	0.50	8	yes
F	03	2.0	F	03	2.0	0.50	F	03	2.0	0.50	8	no
							F	03	3.0	0.30	8	no
							F	03	3.0	0.50	4	no
							F	03	3.0	0.50	6	no
***F*[1]**	***03***	***3.0***	***F*[2]**	***03***	***3.0***	***0.50***	***F*[3]**	***03***	***3.0***	***0.50***	***8***	***no***
							F	03	3.0	0.50	10	no
			F	03	3.0	0.70	F	03	3.0	0.75	8	no
							F	03	3.0	0.50	8	yes
F	03	4.0					F	03	4.0	0.50	8	no
F	04	3.0	F	04	3.0	0.50	F	04	3.0	0.50	8	no
F	06	3.0	F	06	3.0	0.50	F	06	3.0	0.50	8	no
LD	02	3.0	LD	02	3.0	0.50	LD	02	3.0	0.50	8	no
							LD	02	3.0	0.50	8	yes
LD	03	3.0	LD	03	3.0	0.50	LD	03	3.0	0.50	8	no
							LD	03	3.0	0.50	8	yes
LD	04	3.0	LD	04	3.0	0.50	LD	04	3.0	0.50	8	no
Injet	02	3.0	Injet	02	3.0	0.50	Injet	02	3.0	0.50	8	no
Injet	03	3.0	Injet	03	3.0	0.50	Injet	03	3.0	0.50	8	no
Injet	04	3.0	Injet	04	3.0	0.50	Injet	04	3.0	0.50	8	no
Injet	06	3.0										

Reference spray application *[1]* with the PDPA laser, *[2]* in the wind tunnel and *[3]* in the field; F, Hardi ISO standard flat fan nozzles; LD, Hardi ISO low-drift nozzles; Injet, Hardi ISO Injet air inclusion nozzles

With the PDPA laser (Chapter 3), different droplet size and velocity characteristics have been measured for different combinations of nozzle type, size and spray pressure. In the wind tunnel (Chapter 4), fallout and airborne drift deposits were measured and drift potentials (*DP*) were calculated for approximately the same nozzle-pressure combinations. Also the effect of nozzle height and wind speed was investigated. Finally, realistic drift values were obtained directly under field conditions again for the same nozzle-pressure combinations and also for varying boom heights, driving speeds and with or without the use of air assistance (Chapter 5).

Most of the application techniques were tested at the different levels. The reference spray application was always defined as a Hardi ISO F 110 03 standard flat fan nozzle at a pressure of 3.0 bar with a nozzle or boom height of 0.50 m and a driving speed of 8 $km.h^{-1}$ without the use of air assistance (driving speed and air assistance only applicable for field measurements). In this way, it was possible to calculate drift potential reduction percentages (*DPRP*) - based on the wind tunnel measurements - and total drift reduction potentials (DRP_t) - based on the field drift measurements - for the different spray application techniques by comparison with the reference spraying under the same conditions.

In this chapter, a comparison is made between the results obtained with the indirect drift assessment means, i.e. PDPA laser and wind tunnel, and the direct drift assessment method, which are the field drift measurements, to evaluate the potential of these three different drift assessment means. Part of these results were published in Nuyttens *et al.* (2006 e, 2008 a).

6.2. Relations between droplet characteristics, *DPRP* and DRP_t values

6.2.1. Wind tunnel DPRP and field measurement DRP_t values

Drift potential reduction percentages, $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$ resulting from the wind tunnel measurements are presented and described in detail in section 4.3 for the different spray application techniques listed in Table 6.1. Similarly, total drift reduction potentials (DRP_t) for the different spray applications tested in the field are described in detail in section 5.3.2 and summarised in Annex 16.

6.2.1.1. Nozzle type and size

In Figure 6.1, DRP_t values are compared with $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$ values for 10 different Hardi nozzle types tested at a pressure of 3.0 bar and a nozzle or boom height of 0.50 m. The simple linear regressions and their corresponding R^2 values are presented.

From this graph, it is clear that there is a fairly good linear relation between DRP_t and *DPRP* values for these spray application techniques with R^2 values of 0.66, 0.81 and 0.88, respectively for, $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$. The deviation of the first-order regression lines from the bisector is mainly caused by the leverage effect and the results of the F 110 02 nozzle with its relatively high *DPRP* values (ranging from -73.0 to -57.9%) compared with the corresponding DRP_t value of -136.5%. This means that based on the wind tunnel measurements, the driftability of this nozzle type is underestimated compared with the results from the field measurements. Despite this considerable difference between

DRP_t and *DPRP* values for this nozzle type, differences are statistically non-significant ($\alpha = 0.05$) because of the high standard deviations.

Besides the relatively high R^2 values, the correlation between DRP_t values and the different *DPRP* values is significant at the 0.01 level with Pearson coefficients of correlation of 0.815, 0.900 and 0.939, respectively for, $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$. Based on the R^2 values and the corresponding Pearson coefficients of correlations, it can be concluded that there is a fairly good correlation between field drift DRP_t and wind tunnel *DPRP* values although there are some important discrepancies which are discussed below. The best agreement between DRP_t and *DPRP* results was found for the $DPRP_H$ values followed by $DPRP_{V2}$ and $DPRP_{V1}$. Hence, from the three wind tunnel approaches described in section 4.3.2, the approach calculating the surface under the measured fallout deposit curve, is in general best suited to represent real near-field sedimenting drift characteristics. From this point, mainly $DPRP_H$ values are taken into consideration.

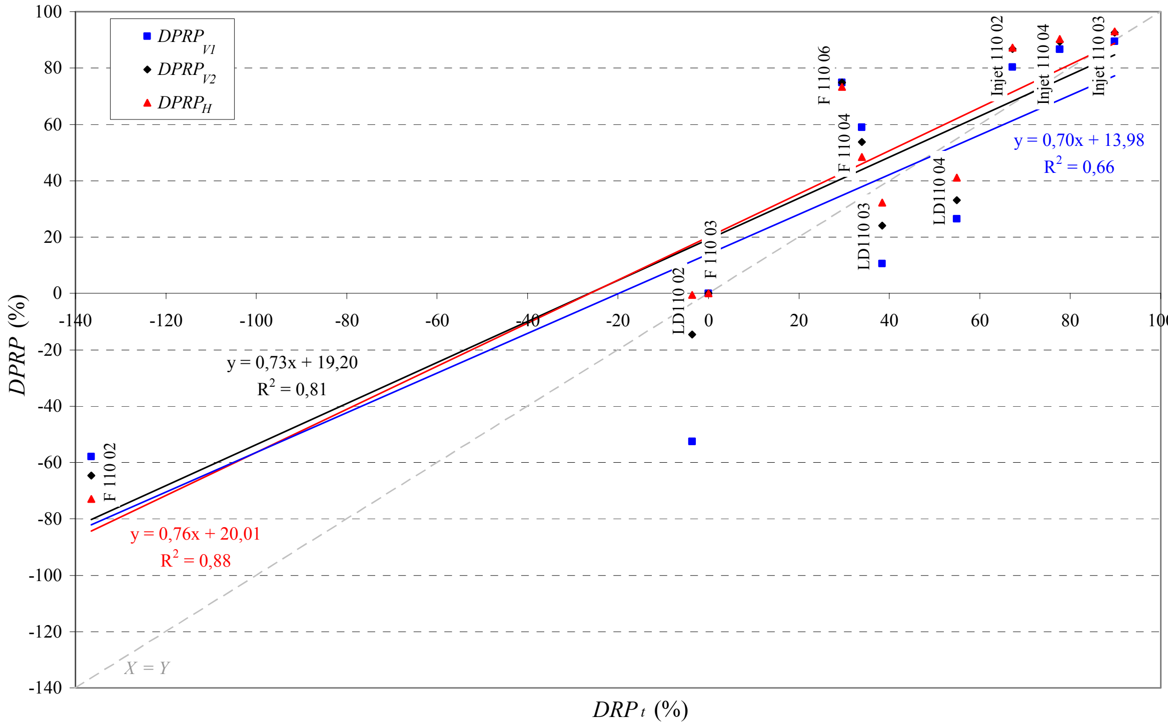

Figure 6.1: Comparison between *DRP* values and $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$ values for different Hardi ISO nozzle types (F, standard flat fan; LD, low-drift; Injet, air inclusion) and sizes (ISO 02, 03, 04 and 06) all at a spray pressure of 3.0 bar and a nozzle or boom height of 0.50 m

Besides the considerable difference between *DPRP* and DRP_t values for the F 110 02 nozzle, some other discrepancies between wind tunnel and field results are observed which are important to keep in mind when interpreting wind tunnel results. Among the other standard flat fan nozzles, a considerable and statistically significant difference between DRP_t and *DPRP* values is also observed for the F 110 06 nozzle with a DRP_t of 29.5% and a $DPRP_H$ of 73.3%. Although for the ISO 03 and ISO 04 standard flat fan nozzles, there is a good agreement between DRP_t and *DPRP* values, it can be seen that *DPRP* values are generally higher than DRP_t values for the standard flat fan nozzles. Knowing that for the standard flat fan nozzles, $DPRP_{V1}$ values were the highest followed by $DPRP_{V2}$ and $DPRP_H$ (§ 4.3.3), it is clear that $DPRP_H$ corresponds best with DRP_t results.

For the different sizes of low-drift nozzles, a good agreement between wind tunnel and field drift results is found with DRP_t values of -3.6, 38.4 and 54.9% and $DPRP_H$ values of -0.5, 32.3 and 41.1%, respectively for, the LD 110 02, LD 110 03 and the LD 110 04 nozzles. In contrast with the standard flat fan nozzles, *DPRP* values are generally lower than DRP_t values. Because for this nozzle type, $DPRP_{V1}$ values were the lowest followed by $DPRP_{V2}$ and $DPRP_H$ (§ 4.3.3), $DPRP_H$ again corresponds best with DRP_t.

For the Injet 02 and Injet 04 air inclusion nozzles, *DPRP* values are limitedly but significantly ($\alpha = 0.05$) higher than DRP_t values. The statistical significance is mainly caused by the high repeatability of the wind tunnel and field measurements for this type of nozzles. On the other hand, *DPRP* and DRP_t values are almost equal for the Injet 03 nozzles. The Injet 03 was also found to have the lowest driftability followed by the Injet 04 and the Injet 02 nozzles based on the wind tunnel as well as on the field measurements. Note that in contrast with the flat fan and the low-drift nozzles, $DPRP_{V1}$ and $DPRP_{V2}$ values correspond better with DRP_t values than $DPRP_H$ values but differences are limited.

In general, investigating the effect of nozzle type and size at a spray pressure of 3.0 bar, similar trends can be found from the *DPRP* and DRP_t results although there are some important deviations in absolute results as discussed above. For the same nozzle size, air inclusion nozzles have the highest DRP_t and *DPRP* values followed by the low-drift nozzles and the standard flat fan nozzles. Only for the LD 110 04 nozzles, *DPRP* values were lower than for the F 110 04 nozzles which was not the case for the DRP_t values.

For the standard and the low-drift flat fan nozzles, bigger ISO nozzle sizes correspond with higher DRP_t and *DPRP* values. Again, one exception was found namely, DRP_t of the F 110 06 nozzle was lower than the DRP_t value of the F 110 04 nozzle type which was not the case for the *DPRP* values.

6.2.1.2. Spray pressure and nozzle height

Besides the experiments with different nozzle types and sizes, a very limited number of measurements were performed with different nozzle or boom heights and spray pressures in the wind tunnel as well as in the field.

As presented in Table 6.1, wind tunnel experiments with an increased nozzle height of 0.70 m and field experiments with an increased boom height of 0.75 m (at the reference speed of 8 $km.h^{-1}$) were carried out with the reference nozzle-pressure combination (F 110 03 at 3.0 bar). These experiments resulted in a $DPRP_H$ value of -131% (§ 4.3.6) and a DRP_t value of -49.9% (§ 5.3.2.8). Despite the fact that downwind spray deposits increase in both cases with an increasing nozzle or boom height, an important difference between $DPRP_H$ and DRP_t values is observed. $DPRP_H$ is much lower compared with DRP_t although the increase in nozzle height in the wind tunnel was slightly less than the increase in boom height in the field. This means that based on the wind tunnel results, the amount of downwind spray deposits is overestimated compared with the results from the field measurement. As mentioned before, for a boom height of 0.50 m, $DPRP_H$ values were higher than DRP_t values for the standard flat fan nozzles (§ 6.2.1.1) while opposite results are found at a height of 0.70 m. This indicates that the amount of downwind spray deposits is much more sensitive to an increase in nozzle height in the wind tunnel than to a similar increase in boom height under real field conditions.

The results from the wind tunnel and the field measurements at a reduced spray pressure of 2.0 bar with the reference nozzle F 110 03 at a nozzle or boom height of 0.50 m, are totally contradictory. Reducing spray pressure from 3.0 to 2.0 bar in the wind tunnel resulted in an increase of downwind spray deposits with $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_{H}$ values of, respectively, -74.6, -48.4 and -34.1% (§ 4.3.5). This could be explained by the fact that reducing pressure from 3.0 to 2.0 bar for this nozzle type, has no significant effect on droplet sizes and reduces droplet velocities slightly. However, the amounts of sedimenting spray drift decreased with a decrease in spray pressure under field conditions (DRP_t = 43.1%, § 5.3.2.6).

More experiments at a wider range of spray pressures are necessary to explain this difference between wind tunnel and field results but it indicates that different mechanisms might have an effect on downwind deposits.

6.2.2. Droplet characteristics and field measurement DRP_t values

Different droplet size and droplet velocity characteristics resulting from the PDPA laser measurements are presented and discussed in detail in sections 3.3.2 and 3.3.3 for the different nozzle-pressure combinations described in Table 6.1. Similarly, total drift reduction potentials (DRP_t) for the different nozzle-pressure combinations tested in the field at a speed of 8 $km.h^{-1}$ and a boom height of 0.50 m are described in detail in section 5.3.2 and summarised in Annex 16. In this section, the relation between the droplet characteristics of the different nozzle-pressure combinations and the corresponding DRP_t values, is investigated.

6.2.2.1. Individual droplet characteristics

First-order linear regressions were performed for the different individual droplet size and velocity characteristics (Table 3.3, Table 3.4 and Table 3.5) with the different droplet characteristics as the independent variable and DRP_t as the dependent variable. This was done to investigate the importance of the different individual droplet characteristics on DRP_t values, representing the amount of sedimenting spray drift under field conditions. In Table 6.2, the coefficients of determination (R^2) are presented for the different droplet characteristics together with the intercepts and slopes in cases where the linear relation was significant at a level α of 0.05 (F test).

From these results, it is clear that droplet size as well as droplet velocity characteristics are related with DRP_t values. Only in some particular cases (e.g. $D_{v0.5}/NMD$, v_{vol75}, v_{vol90} and v_{avg}) the (linear) relationship was not significant (α= 0.05). As expected, DRP_t values generally increase with increasing values of droplet diameter (e.g. $D_{v0.25}$, D_{20}, NMD) and droplet velocity characteristics (e.g. v_{vol25}) which can be deduced from the corresponding positive b_0 values. On the other hand, DRP_t values decrease with increasing percentages of small droplets (e.g. V_{100}) which can be concluded from the negative b_0 values.

Table 6.2: Characteristics of first-order linear regressions of the form $DRP_t = a_0 + b_0.X$ with the different droplet characteristics as the independent variable (X) and DRP_t as the dependent variable

X	R^2	a_0	b_0	X	R^2	a_0	b_0
$D_{v0.1}$ (µm)*	0.50	-83.6	0.56	V_{200} (%)***	0.78	100.7	-4.24
$D_{v0.25}$ (µm)**	0.51	-93.6	0.44	V_{250} (%)***	0.77	107.0	-2.80
$D_{v0.5}$ (µm)**	0.54	-107.8	0.37	NMD (µm)**	0.41	-93.2	1.30
$D_{v0.75}$ (µm)**	0.58	-133.9	0.35	$D_{v0.5}/NMD$	0.01		
$D_{v0.9}$ (µm)**	0.60	-177.5	0.39	RSF*	0.35	213.1	-196.6
D_{10} (µm)*	0.46	-92.4	0.91	v_{vol10} ($m.s^{-1}$)*	0.49	-88.0	87.8
D_{20} (µm)*	0.48	-90.0	0.68	v_{vol25} ($m.s^{-1}$)*	0.47	-89.8	45.7
D_{30} (µm)*	0.49	-94.4	0.55	v_{vol50} ($m.s^{-1}$)*	0.42	-116.6	32.2
D_{32} (µm)**	0.52	-102.7	0.43	v_{vol75} ($m.s^{-1}$)	0.11		
V_{50} (%)***	0.77	87.7	-212.3	v_{vol90} ($m.s^{-1}$)	0.00		
V_{75} (%)***	0.76	91.6	-53.0	v_{avg} ($m.s^{-1}$)	0.11		
V_{100} (%)***	0.72	90.0	-22.0	VSF***	0.68	186.7	-86.2
V_{150} (%)***	0.74	93.3	-7.89				

*/**/***, statistically significant linear relation at a level α of 0.05 (*), 0.01 (**) and 0.001 (***); R^2, coefficient of determination; a_0, b_0, intercept and slope of the first-order linear regression; X, independent variable; $D_{v0.1}$, $D_{v0.25}$, $D_{v0.5}$, $D_{v0.75}$, $D_{v0.9}$, diameter below which smaller droplets constitute 10, 25, 50, 75 and 90% of the total volume; D_{10}, D_{20}, D_{30}, D_{32}, arithmetic, surface, volume and sauter mean diameter; V_{50}, V_{75}, V_{100}, V_{150}, V_{200}, V_{250}, proportion of total volume of droplets smaller than 50, 75, 100, 150, 200 and 250 µm in diameter; NMD, number median diameter; RSF, relative span factor; v_{vol10}, v_{vol25}, v_{vol50}, v_{vol75}, v_{vol90}, droplet velocity below which slower droplets constitute 10, 25, 50, 75 and 90% of the total spray volume; v_{avg}, arithmetic average droplet velocity; VSF, velocity span factor

From the different individual droplet characteristics, V_{200} has the highest predictive power (R^2=0.78, Table 6.2) with regard to DRP_t. This means the proportion of the total volume of droplets smaller than 200 µm in diameter, is the best indicator for the amount of sedimenting spray drift in the field and explains about 78% of the total variation in DRP_t values. Besides V_{200}, the characteristics V_{50}, V_{75}, V_{100}, V_{150} and V_{250} also have a statistically significant linear relation with DRP_t at a level α of 0.001. Other studies also found droplet size to be one of the most influential factors related to drift (Satow *et al.*, 1993; Bird *et al.*, 1996; Carlsen *et al.*, 2006 b) and different researchers have considered droplets smaller than 75 (Miller & Hadfield, 1989; Hobson *et al.*, 1990), 100 (Byass & Lake, 1977; Grover *et al.*, 1978; Bode, 1984), 150 (Yates *et al.*, 1985; Combellack *et al.*, 1996) or 200 µm (Bouse *et al.*, 1990) to be the most drift-prone. On the other hand, Butler Ellis and Bradley (2002) concluded that there is a poor correlation between spray volume contained in droplets smaller than 100 µm and drift which is in contrast with the results from this study. In Figure 6.2, measured DRP_t values (%) are compared with the DRP_t values predicted using the simple first-order linear regression with V_{200} (%) as the independent variable which is:

$$DRP_t = 100.7 - 4.24.V_{200} \qquad (6.1)$$

Moreover, the simple linear regression between measured and predicted DRP_t and their corresponding R^2 values is presented. In Figure 6.4, the relation between DRP_t and V_{200} values, as expressed by formula 6.1, is illustrated.

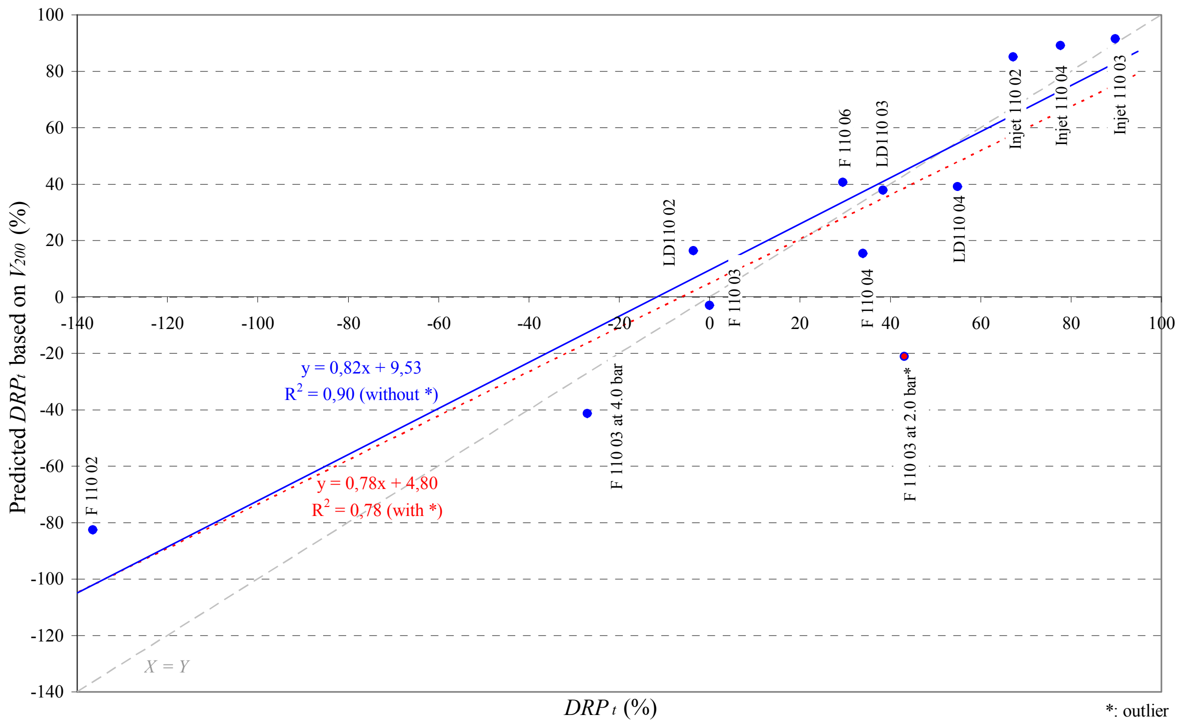

Figure 6.2: Comparison between DRP_t values and predicted DRP_t values based on first-order linear regression with V_{200} as the independent variable for different Hardi ISO nozzle-pressure combinations (F, standard flat fan; LD, low-drift; Injet, air inclusion)

Similar to the results from the wind tunnel experiments (§ 6.2.1.2, Figure 6.1), the slight deviation of the first-order regression line from the bisector in Figure 6.2 is mainly caused by the leverage effect of the F 110 02 nozzle with its relatively high predicted DRP_t value compared with the measured DRP_t. Only in one case, namely the F 110 03 at 2.0 bar, an important difference between measured and predicted DRP_t values is found. Based on field measurements, the amount of sedimenting spray drift decreased with a decrease in spray pressure from 3.0 to 2.0 bar (DRP_t =43.1%) despite the fact that the proportion of droplets smaller than 200 µm slightly increased with this decrease in spray pressure resulting in a predicted DRP_t value based on V_{200} of -21.1%. Similar contradictory results were already observed for this nozzle-pressure combination comparing *DPRP* and DRP_t values in section 6.2.1.2. Without this outlier, an R^2 of 0.90 between measured DRP_t values and predicted DRP_t based on V_{200} (Figure 6.2) is found. As described in section 6.2.1.1, R^2 values between DRP_t on the one hand and $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$ on the other hand were respectively, 0.66, 0.81 and 0.88. Hence, the indirect drift assessment method measuring V_{200} values is at least as well suited to represent near-field drift characteristics as the wind tunnel approach calculating $DPRP_H$ values and even better suited than the wind tunnel approaches calculating $DPRP_{V1}$ and $DPRP_{V2}$ values. On the other hand, with the PDPA laser measurements, it is only possible to investigate the effect of nozzle type, size and spray pressure whereas the effect of nozzle height can also be investigated by means of wind tunnel measurements. In section 6.2.2.2, the possibility to combine several droplet characteristics to come to an even better prediction of DRP_t, is considered.

Looking into detail to Figure 6.2, it can be observed that besides the considerable differences between measured and predicted DRP_t values for the F 110 03 at 2.0 bar and for the F 110 02, there are some other, smaller deviations. For example, for the standard flat fan nozzles, predicted DRP_t based on V_{200} is higher for the F 110 06 compared to the F 110 04 while opposite results were found based on the field measurements. Again, the Injet 03 is found to have the highest DRP_t based on the droplet size characteristics (V_{200}) as well as on the field drift experiments. Using formula 6.1, which is illustrated in Figure 6.4, the effect of the proportion of the total volume of droplets smaller than 200 μm (V_{200}) on DRP_t can be calculated. For example, an increase of V_{200} from 10 to 30% results in a decrease of DRP_t from about 58% down to -27% corresponding with an increase of the total amount of near-field sedimenting spray drift with a factor of about 3.0 (formula 5.11).

Besides the droplet size characteristics V_{50}, V_{75}, V_{100}, V_{150}, V_{200} and V_{250}, there was one more droplet characteristic with a statistically significant linear relation with DRP_t at a level α of 0.001, namely *VSF* (Table 6.1) with an R^2 of 0.68. This velocity span factor is a dimensionless parameter indicative of the uniformity of the drop size velocity distribution and is calculated based on v_{vol10}, v_{vol50} and v_{vol90} (formula 3.8). The higher the *VSF* value, representing a less uniform droplet velocity distribution, the lower the DRP_t value and hence, the higher the driftability. This might seem surprising at first sight but as described in detail in Chapter 3, there is a clear relation between droplet sizes and droplet velocities which is reflected in the *VSF* values. From the different nozzle types, air inclusion nozzles have the lowest *VSF* values followed by the low-drift and the standard flat fan nozzles. The low *VSF* values for the air inclusion nozzles can be explained by the relatively high v_{vol10} values (because of the low proportion of small droplets) and the relatively low v_{vol90} values (because of the low ejection velocities) as described in detail in section 3.3.3. Moreover, for the standard and the low-drift flat fan nozzles, *VSF* values decrease with increasing nozzle sizes; for the air inclusion nozzles, no significant effect of nozzle size on *VSF* values is found.

From the other droplet velocity characteristics, a statistically significant linear relation at a level α of 0.05 was found for v_{vol10}, v_{vol25}, v_{vol50} with R^2 values of 0.49, 0.47 and 0.42 and DRP_t values increase with an increase in v_{vol10}, v_{vol25} and v_{vol50} values. As described in section 3.3.3, these slower droplet velocity characteristics are related with the proportion of small droplets and hence with the amount of spray drift. Other droplet velocity characteristics - v_{vol75}, v_{vol90} and v_{avg} - are not related to the amount of small droplets and hence neither with DRP_t values (R^2 values of respectively 0.11, 0.00 and 0.11). Ozkan (1998) also found that an increase of the downward droplet velocity decreases drift distances.

Finally, looking at the other droplet size characteristics ($D_{v0.1}$, $D_{v0.5}$, D_{10}, D_{32}, *NMD*, etc.) - including the most commonly used descriptor of droplet size, namely volume median diameter ($D_{v0.5}$) - most of them are also significantly related to DRP_t but their predictive power is less good compared to V_{50}, V_{75}, V_{100}, V_{150}, V_{200}, V_{250} and *VSF*.

6.2.2.2. Multiple linear regression

The potential of a multiple linear regression to come to an improved prediction of DRP_t based on the different droplet characteristics was investigated, although it was already found that it was possible to come to a good prediction of DRP_t using a first-order linear regression with V_{200} (%) as the independent variable (§ 6.2.2.1).

The Pearson correlation matrix of the different droplet size characteristics is presented in Annex 19. This correlation matrix already indicates that the different droplet characteristics - with a statistically significant linear relation at a level α of 0.05 with DRP_t - are correlated. Logically, the different droplet size characteristics are mutually correlated just as the different droplet velocity characteristics.

As already mentioned several times before, the different statistically significant droplet velocity characteristics (v_{vol10}, v_{vol25}, v_{vol50}, *VSF*) are also correlated to the droplet size characteristics. On the one hand, this can be explained by the fact that after ejection from the nozzle, droplets are decelerated as a result of air resistance and smaller droplet sizes slow down more rapidly compared to bigger droplets due to the effect of air drag. On the other hand, droplet ejection velocities at the exit of the nozzle are within the same range of magnitude for the different conventional nozzles tested in this research within a limited pressure range from 2.0 to 4.0 bar. It can be assumed that a different relation between droplet velocities and sizes would be found in case of using less conventional spray application techniques like air assistance (§ 2.2.2.3) or twin fluid nozzles (§ 2.2.1.3). For the droplet characteristics which were not related with DRP_t at a level α of 0.05 like v_{vol75}, v_{vol90}, v_{avg} and $D_{v0.5}/NMD$, no correlation with other characteristics was found.

A forward stepwise regression procedure (using SPSS 10.0.1) was used to select the "best" linear regression model out of the large pool of potential independent variables. The F statistic was used as the criterion for adding or deleting an *X* variable. With this method, an *X* variable was brought into the model when the probability of F was below 0.05 and dropped when the probability of F exceeded 0.10. This procedure resulted again in the first-order linear model with V_{200} as the independent variable (formula 6.1), even when the probability of the critical F value was increased up to 0.15. Hence, it was concluded that this simple first-order linear model is best suited to predict DRP_t values for the different conventional spray applications tested in this research, not including air assistance or twin fluid nozzles.

6.2.3. Droplet characteristics and wind tunnel DPRP values

In this section, the relation between the droplet characteristics of the different nozzle-pressure combinations and the corresponding drift potential reduction percentages (*DPRP*) is evaluated (Table 6.1). Three different wind tunnel approaches were followed to calculate drift potential resulting in $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$ as described in section 4.3.2.

6.2.3.1. Individual droplet characteristics

First-order linear regressions were performed with the different droplet size and velocity characteristics (§ 3.3.2 and 3.3.3) as the independent variable and $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$ as the dependent variables. Results are presented in Table 6.3. This was done to investigate the importance of the different individual droplet characteristics on *DPRP* values, representing the amount of downwind spray deposits during the wind tunnel measurements.

Looking at differences between $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$, it can be seen that the different individual droplet size characteristics are generally best related with $DPRP_H$ followed by $DPRP_{V2}$ and $DPRP_{V1}$. For example, for V_{200}, R^2 values of 0.92, 0.84 and 0.69 were found, respectively for, $DPRP_H$, $DPRP_{V2}$ and $DPRP_{V1}$. Again, *DPRP* values generally increase with increasing droplet diameter characteristics (e.g. $D_{v0.25}$, D_{20}, *NMD*) and with increasing percentages of small droplets (e.g. V_{100}).

Table 6.3: Characteristics of first-order linear regressions ($Y = a_0 + b_0.X$) with the droplet characteristics as the independent variable (X) and $DPRP_{V1}$, $DPRP_{V2}$, $DPRP_H$ as the dependent variable (Y)

	$DPRP_{V1}$			$DPRP_{V2}$			$DPRP_H$		
X	**R²**	**a_0**	**b_0**	**R²**	**a_0**	**b_0**	**R²**	**a_0**	**b_0**
$D_{v0.1}$ (µm)	0.60**	-100.2	0.63	0.67**	-87.4	0.60	0.68**	-82.3	0.59
$D_{v0.25}$ (µm)	0.61**	-109.9	0.48	0.68**	-96.9	0.46	0.69**	-92.1	0.46
$D_{v0.5}$ (µm)	0.62**	-123.4	0.40	0.71***	-110.3	0.39	0.72***	-105.5	0.38
$D_{v0.75}$ (µm)	0.69**	-154.3	0.39	0.78***	-139.4	0.37	0.79***	-134.0	0.37
$D_{v0.9}$ (µm)	0.78***	-208.5	0.44	0.86***	-188.8	0.42	0.86***	-181.4	0.41
D_{10} (µm)	0.50*	-99.8	0.94	0.57**	-88.3	0.91	0.59**	-84.0	0.90
D_{20} (µm)	0.54**	-101.0	0.73	0.61**	-88.9	0.70	0.62**	-84.3	0.69
D_{30} (µm)	0.57**	-107.4	0.63	0.64**	-94.9	0.61	0.65**	-90.1	0.60
D_{32} (µm)	0.63**	-120.2	0.47	0.70***	-106.6	0.45	0.71***	-101.5	0.43
V_{50} (%)	0.57**	76.0	-191.5	0.73***	85.0	-196.2	0.82***	89.5	-202.1
V_{75} (%)	0.69**	87.0	-55.4	0.84***	94.8	-55.5	0.91***	98.7	-56.4
V_{100} (%) ***	0.71***	88.4	-24.0	0.86***	95.8	-23.9	0.92***	99.4	-24.2
V_{150} (%)***	0.71***	90.4	-8.35	0.86***	97.8	-8.33	0.92***	101.5	-8.42
V_{200} (%) ***	0.69***	93.5	-4.17	0.84***	101.3	-4.18	0.92***	105.2	-4.24
V_{250} (%)***	0.69***	99.5	-2.73	0.84***	107.0	-2.72	0.90***	110.9	-2.75
NMD (µm)**	0.42*	-95.2	1.30	0.49*	-84.4	1.26	0.50*	-80.4	1.25
$D_{v0.5}/NMD$	0.04			0.02			0.01		
RSF	0.25			0.38			0.37*	217.2	-195.3
v_{vol10} ($m.s^{-1}$)	0.86***	-126.1	115.3	0.84***	-103.1	103.4	0.80***	-94.0	98.5
v_{vol25} ($m.s^{-1}$)	0.81***	-127.9	59.8	0.80***	-105.4	53.9	0.77***	-96.8	51.6
v_{vol50} ($m.s^{-1}$)	0.71***	-156.2	40.9	0.69**	-129.1	36.4	0.68**	-120.8	35.2
v_{vol75} ($m.s^{-1}$)	0.32			0.28			0.28		
v_{vol90} ($m.s^{-1}$)	0.07			0.05			0.04		
v_{avg} ($m.s^{-1}$)	0.38*	-135.8	95.9	0.31			0.28		
VSF	0.83***	209.7	-102.3	0.90***	206.2	-96.2	0.91***	205.6	-94.3

*/**/***, statistically significant linear relation at a level α of 0.05 (*), 0.01 (**) and 0.001 (***); R^2, coefficient of determination; a_0, b_0, intercept and slope of the first-order linear regression; *X*, independent variable; $D_{v0.1}$, $D_{v0.25}$, $D_{v0.5}$, $D_{v0.75}$, $D_{v0.9}$, diameter below which smaller droplets constitute 10, 25, 50, 75 and 90% of the total volume; D_{10}, D_{20}, D_{30}, D_{32}, arithmetic, surface, volume and sauter mean diameter; V_{50}, V_{75}, V_{100}, V_{150}, V_{200}, V_{250}, proportion of total volume of droplets smaller than 50, 75, 100, 150, 200 and 250 µm in diameter; *NMD*, number median diameter; *RSF*, relative span factor; v_{vol10}, v_{vol25}, v_{vol50}, v_{vol75}, v_{vol90}, droplet velocity below which slower droplets constitute 10, 25, 50, 75 and 90% of the total spray volume; v_{avg}, arithmetic average droplet velocity; *VSF*, velocity span factor

On the other hand, the individual droplet velocity characteristics, like v_{vol10} v_{vol25} and v_{vol50}, are best related with $DPRP_{V1}$ followed by $DPRP_{V2}$ and $DPRP_H$ although differences are rather limited. For example, for v_{vol10}, R^2 values decreased from 0.86 to 0.84 and 0.80, respectively for, $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$. As expected, *DPRP* values generally increase with increasing values of droplet velocity characteristics ($b_0>0$). This indicates that droplet size characteristics are more related with fallout deposits compared with airborne deposits while the opposite is found for the droplet velocity characteristics. The droplet velocity characteristic *VSF*, although calculated based on v_{vol10}, v_{vol50} and v_{vol90}, is best related to $DPRP_H$ (R^2= 0.91) and its R^2 values are higher than the R^2 values of the other droplet velocity characteristics.

Looking into detail to $DPRP_H$, which corresponds best with real field DRP_t values (§ 6.2.1), V_{100}, V_{150} and V_{200} have the highest predictive power with regard to $DPRP_H$ with in each case an R^2 value of 0.92. The characteristics V_{50}, V_{75} and V_{250} also have a statistically significant linear relation with $DPRP_H$ at a level α of 0.001. As mentioned in section 6.2.2.1, V_{200} was also found to be the best indicator for DRP_t representing the amount of sedimenting spray drift in the field with a comparable R^2 value of 0.90 leaving away the outlier. The following first order linear regression between $DPRP_H$ and V_{200} was found:

$$DPRP_H = 105.2 - 4.24.V_{200} \qquad (6.2)$$

Remark the striking correspondence between this formula and formula 6.1, again confirming the similarities between $DPRP_H$ values resulting from wind tunnel measurements and DRP_t values from the field measurements. Analogous to DRP_t, the linear relation between the droplet size characteristic V_{200} and $DPRP_H$ (formula 6.2) is presented in Figure 6.4. Again, the good correspondence between DRP_t and $DPRP_H$ can be seen. Similarly with DRP_t, an increase of V_{200} from 10 to 30% results in a decrease of $DPRP_H$ from about 62% down to -22% corresponding with an increase of the total amount of downwind fallout deposits in the wind tunnel with a factor of about 3.2 (formula 5.11).

In Figure 6.3, measured $DPRP_H$ values (%) are compared with the predicted $DPRP_H$ values using formula 6.2 and the linear regression between measured and predicted $DPRP_H$ values is presented. An R^2 of 0.91 between both variables was found. Hence, for the different spray applications, a good correlation exists between measured and predicted $DPRP_H$ values, also for the F 110 03 at 2.0 bar which was found to be an extreme outlier based on its DRP_t value (§ 6.2.1.2 and § 6.2.2.1). This means that for this nozzle-pressure combination, the $DPRP_H$ value measured in the wind tunnel is in correspondence with the measured droplet characteristics which is not the case for the DRP_t values from the field measurements. Again, more experiments are necessary to explain this contradiction.
Besides V_{50}, V_{75}, V_{100}, V_{150}, V_{200} and V_{250}, some other droplet characteristics were found with a statistically significant linear relation with $DPRP_H$ at a level α of 0.001, namely $D_{v0.5}$, $D_{v0.75,}$ $D_{v0.9}$, v_{vol10}, v_{vol25} and *VSF* (Table 6.3).

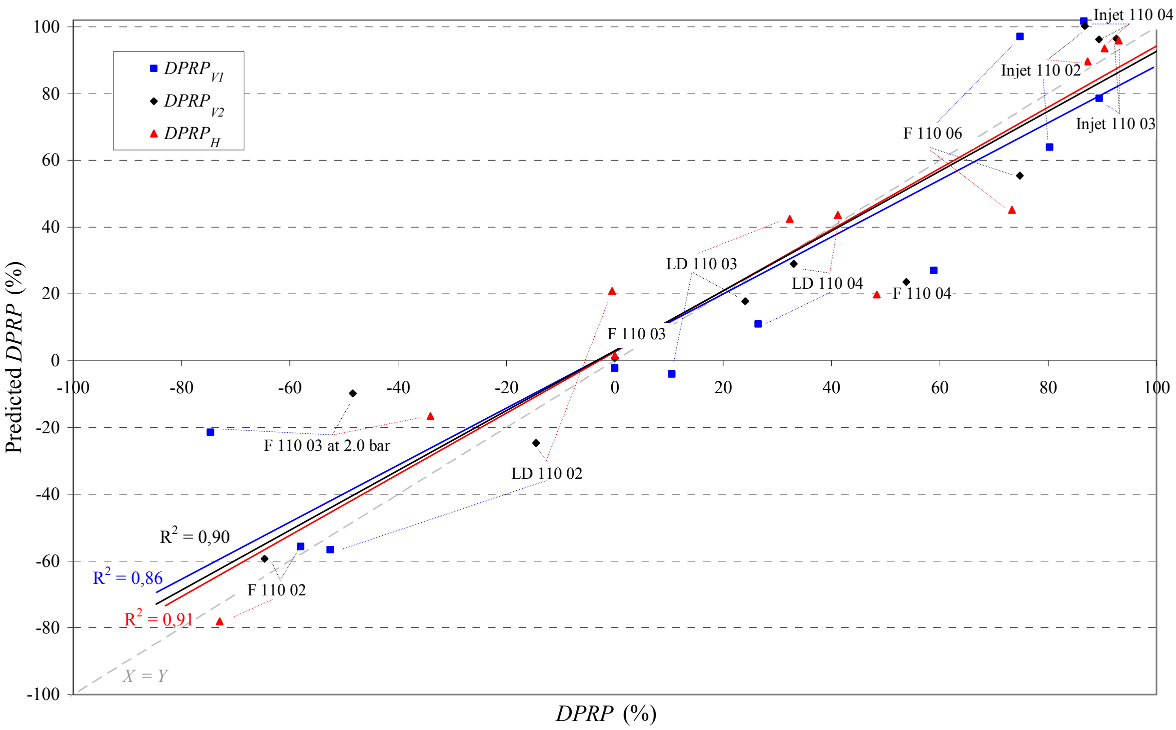

Figure 6.3: Comparison between measured and predicted $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$ values using formulas 6.2, 6.3 and 6.4.

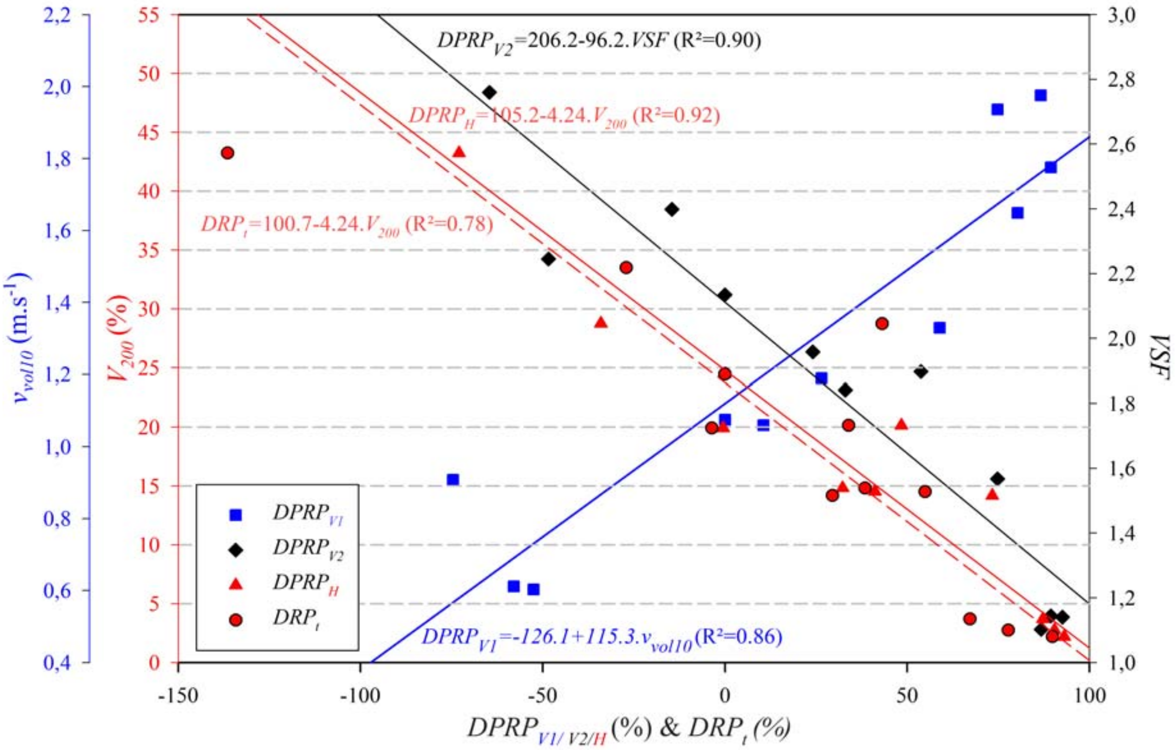

Figure 6.4: Relation between the drift characteristics $DPRP_{V1}$, $DPRP_{V2}$, $DPRP_H$ and DRP_t and the corresponding droplet characteristic with the highest predictive power, respectively v_{vol10}, VSF, V_{200} and V_{200} together with the corresponding first order linear regressions and their R² values

While DRP_t and $DPRP_H$ were related most with the droplet size characteristic V_{200}, $DPRP_{V1}$ and $DPRP_{V2}$ were related most with one of the droplet velocity characteristics namely v_{vol10} for $DPRP_{V1}$ (R^2= 0.86) and VSF for $DPRP_{V2}$ (R^2= 0.90). In Figure 6.3, measured $DPRP_{V1}$ and $DPRP_{V2}$ values (%) are compared with the predicted $DPRP_{V1}$ and $DPRP_{V2}$ values using the following first-order linear regressions:

$$DPRP_{V1} = -126.1 + 115.3.v_{vol10} \quad (6.3)$$

$$DPRP_{V2} = 206.2 - 96.2.VSF \quad (6.4)$$

Based on these first-order regressions, also illustrated in Figure 6.4, Pearson coefficients of correlation between measured and predicted $DPRP_{V1}$ and $DPRP_{V2}$ values of respectively 0.926 and 0.947 were found. This means that droplet velocity characteristics have a higher predictive power than the droplet size characteristics with regard to $DPRP_{V1}$ and $DPRP_{V2}$ which can be explained among others by the fact that there is an important link between droplet sizes and droplet velocities because larger droplets retain their momentum for longer. As described in section 3.3.3, droplet velocity characteristics like v_{vol10} and v_{vol25} are related with the proportion of small droplets. That is why higher v_{vol10} and v_{vol25} values correspond with higher $DPRP$ values and thus with a lower driftability (formula 6.3 and Table 6.3). On the other hand, higher VSF values, expressing a less uniform droplet velocity distribution, correspond with lower $DPRP$ values (formula 6.4 and Table 6.3). Also in case of $DPRP_H$, a significant linear relation at a level α of 0.001 was found with droplet velocity characteristics v_{vol10}, v_{vol25} and VSF. For the 'faster' droplet velocity characteristics like v_{vol75}, v_{vol90} and v_{avg} the (linear) relationship was generally not significant (α= 0.05). Other generally non-significant droplet characteristics are $D_{v0.5}/NMD$ and RSF (Table 6.3).

Considering $DPRP_{V1}$, which was best related with v_{vol10}, different other droplet characteristics were found with a statistically significant linear relation at a level α of 0.001, namely $D_{v0.9}$, V_{100}, V_{150}, V_{200}, V_{250}, v_{vol25}, v_{vol50} and VSF. For $DPRP_{V2}$, the other statistical significant variables at a level α of 0.001 were $D_{v0.75}$, $D_{v0.9}$, D_{32}, V_{50}, V_{100}, V_{150}, V_{200}, V_{250}, v_{vol10} and v_{vol25} but their predictive power is less good compared to VSF.

Using formulas 6.3 and 6.4, both illustrated in Figure 6.4, the effect of variations in droplet velocity characteristics on $DPRP_{V1}$ and $DPRP_{V2}$ can be calculated. For example, an increase of v_{vol10} from 0.5 to 1.5 $m.s^{-1}$ results in an increase of $DPRP_{V1}$ from about -68% up to about 47%. A comparable increase in $DPRP_{V2}$ values corresponds with a decrease in VSF values from about 2.8 to 1.6.

In Figure 6.3, there is a better correspondence between the first-order regression lines and the 'ideal' bisector compared with the regressions presented in Figure 6.1 (DRP_t versus $DPRP$) and Figure 6.2 (DRP_t versus predicted DRP_t). This confirms the fact that these deviations are mainly caused by the leverage effect of the low DRP_t value of the F 110 02 nozzle. Hence, for the F 110 02 nozzle, the wind tunnel $DPRP$ values as well as the predicted DRP_t and $DPRP$ values based on the droplet characteristics are limitedly higher than the measured DRP_t value in the field which was -136.5%.

Looking into more detail at Figure 6.3, it can be observed that despite the generally good correlation between measured and predicted $DPRP$ values, there are some small deviations. For example, for the F 110 03 nozzle at 2.0 bar, all predicted $DPRP$ values are higher than the measured $DPRP$ values while the opposite was found for the F 110 04 nozzle. For the F 110 06 nozzle, predicted values of $DPRP_H$ and $DPRP_{V2}$ are lower than the measured ones, while the predicted value of $DPRP_{V1}$ was higher than the measured one.

In general, it can be concluded that different droplet size as well as droplet velocity characteristics are related with *DPRP* values keeping in mind that droplet size and droplet velocity characteristics are also mutually correlated. The droplet characteristics with generally the highest predictive power with regard to *DPRP* were the droplet size characteristics V_{75}, V_{100}, V_{150}, V_{200} and V_{250} and the droplet velocity characteristics v_{vol10}, v_{vol25} and *VSF*, although some important differences between the three wind tunnel approaches ($DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$) were observed.

6.2.3.2. Multiple linear regression

Analogous to DRP_t, the possibilities of a multiple linear regression to come to an improved prediction of $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$ were investigated following the same procedure as described in section 6.2.2.2.

For $DPRP_{V1}$ and $DPRP_{V2}$, it could be concluded that similarly to DRP_t, the simple first-order linear models described by formulas 6.3 and 6.4 are best suited to predict $DPRP_{V1}$ and $DPRP_{V2}$. However, for the prediction of $DPRP_H$, the forward stepwise regression procedure also retained v_{vol10} as a second independent variable (probability of $F \leq 0.05$) besides V_{200} despite the relatively high intercorrelation between both variables. A Pearson coefficient of correlation of 0.80 between V_{200} and v_{vol10} was found (Annex 19). The regression procedure resulted in the following multiple linear regression model with an R^2 of 0.96 to predict wind tunnel $DPRP_H$ values based on droplet characteristics V_{200} and v_{vol10}.

$$DPRP_H = 31.0 - 2.94.V_{200} + 40.4.v_{vol10} \quad (6.5)$$

From this formula, it can be concluded that the amount of fallout deposits in the wind tunnel (expressed by $DPRP_H$) increases with an increase of the proportion of the total volume of droplets smaller than 200 µm as well as with a decrease of the v_{vol10} droplet velocity.

In Figure 6.5, measured $DPRP_H$ values (%) are compared with the predicted $DPRP_H$ values using the simple first-order linear model (§ 6.2.3.1, formula 6.2) and the multiple linear regression model (formula 6.5). The linear regression between measured and predicted $DPRP_H$ values is presented in both cases. Remember an R^2 of 0.91 was found between the measured and the predicted $DPRP_H$ values using the simple first-order linear model, this coefficient increases up to 0.96 using the multiple linear regression model.

From Figure 6.5, it can be seen that the different measuring points and the corresponding first-order regressions generally shift towards the 'ideal' bisector going from the first order to the multiple linear model. This illustrates the improved predictive power of the multiple linear model compared with the first-order model. Only in case of the Injet 04 nozzle, the multiple linear model resulted in a worse and even physically meaningless $DPRP_H$ prediction.

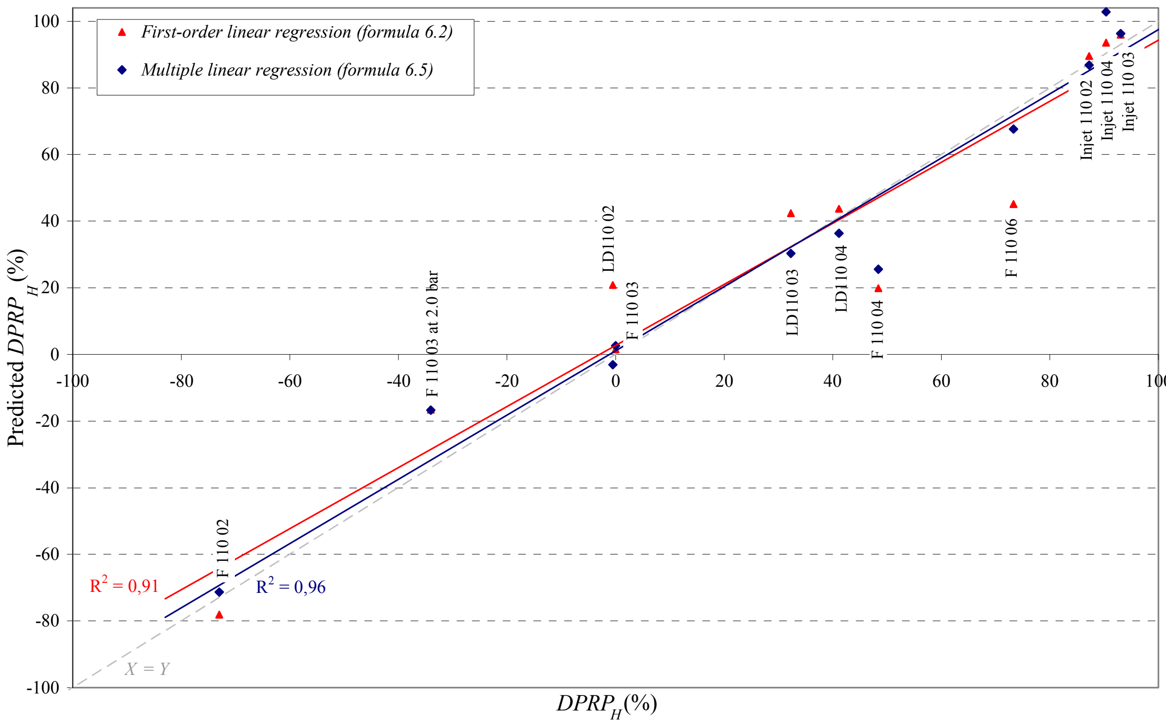

Figure 6.5: Comparison between measured and predicted $DPRP_H$ values using both the simple first-order linear model and the multiple linear model.

In conclusion, the simple first-order linear models described in section 6.2.3.1 are best suited to predict $DPRP_{V1}$ and $DPRP_{V2}$ values. In case of $DPRP_H$, a better prediction was obtained using a multiple linear model with the droplet size characteristic V_{200} and the droplet velocity characteristic v_{vol10} as predictive variables.

6.3. Conclusions

In this finalizing chapter, the results of the three different drift assessment means considered in this work for 13 different nozzle-pressure combinations are compared, to evaluate the potential of the indirect (PDPA laser and wind tunnel measurements) and direct (field drift measurements) drift assessment means.

For these nozzle-pressure combinations, different droplet characteristics were obtained from the PDPA laser measurements. Fallout and airborne drift deposits were measured in the wind tunnel and based on these data, drift potential reduction percentages (*DPRP*) were calculated using three different approaches ($DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$), by comparison with the reference spraying under the same conditions. In a similar way, total drift reduction potentials (DRP_t) were calculated for these nozzle-pressure combinations based on field drift measurements. Moreover, in the field and wind tunnel, a limited series of measurements were performed with varying boom and nozzle heights.

Comparing $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$ of the different nozzle-pressure combinations with the corresponding DRP_t values, it was found that there is a fairly good correlation between field drift DRP_t and wind tunnel *DPRP* values with the best agreement with $DPRP_H$ ($R^2 = 0.88$) followed by $DPRP_{V2}$ ($R^2 = 0.81$) and $DPRP_{V1}$ ($R^2 = 0.66$). This means that the wind tunnel approach, calculating the surface under the measured fallout deposit curve, is best suited to represent real near-field sedimenting drift characteristics and similar trends can be found - concerning the effect of nozzle type, size, height and pressure - from the *DPRP* and DRP_t results although there are some deviations in absolute results mainly for varying spray pressure and nozzle height.

Investigating the relation between individual droplet characteristics and field measurement DRP_t values, it was found that droplet size as well as droplet velocity characteristics are related with DRP_t values. DRP_t values generally increase with increasing values of droplet diameter and droplet velocity characteristics and decrease with increasing percentages of small droplets. Moreover, the proportion of the total volume of droplets smaller than 200 µm in diameter (V_{200}), was found to be the best indicator for the amount of sedimenting spray drift in the field and explains about 78% of the total variation in DRP_t values using the following relation:

$$DRP_t = 100.7 - 4.24.V_{200}$$

Besides this V_{200}, the droplet size characteristics V_{50}, V_{75}, V_{100}, V_{150} and V_{250} and the velocity span factor (*VSF*) were also statistically significant related with DRP_t at a level α of 0.001. The higher the *VSF* value, representing a less uniform droplet velocity distribution, the lower the DRP_t value. This can be explained by the fact that there is a clear relation between droplet sizes and droplet velocities which is reflected in the *VSF* values as described in Chapter 3.

Comparing results from the PDPA laser and the wind tunnel measurements, it can be concluded that the indirect drift assessment method measuring V_{200} values is at least as well suited to represent near-field drift characteristics as the wind tunnel approach calculating $DPRP_H$ values and even better suited than the wind tunnel approaches calculating $DPRP_{V1}$ and $DPRP_{V2}$ values. On the other hand, with the PDPA laser measurements, it is only possible to investigate the effect of nozzle type, size and spray pressure whereas the effect of nozzle height can also be investigated by means of wind tunnel measurements. With both indirect techniques, it is difficult to investigate effects like driving speed and air assistance.

Comparing both indirect drift assessment means, the different individual droplet size characteristics are generally best related with $DPRP_H$ followed by $DPRP_{V2}$ and $DPRP_{V1}$ while the opposite was found for the droplet velocity characteristics. With regard to $DPRP_H$, V_{100}, V_{150} and V_{200} have the highest predictive power with an R^2 value of 0.92, while $DPRP_{V1}$ was related most with v_{vol10} (R^2= 0.86) and $DPRP_{V2}$ with *VSF* (R^2= 0.90). Again, this indicates that droplet sizes and droplet velocities are strongly linked mainly because larger droplets retain their momentum for longer. Moreover, droplet size characteristics are more related with fallout deposits compared to airborne deposits while the opposite is found for the droplet velocity characteristics.
In general, the droplet characteristics with the highest predictive power with regard to *DPRP* were the droplet size characteristics V_{75}, V_{100}, V_{150}, V_{200} and V_{250} and the droplet velocity characteristics v_{vol10}, v_{vol25} and *VSF*, although some important differences between the three wind tunnel approaches ($DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$) were observed.

Finally, first-order linear models were best suited to predict DRP_t, $DPRP_{V1}$ and $DPRP_{V2}$ values respectively based on droplet characteristics V_{200}, v_{vol10} and *VSF*. In case of $DPRP_H$, a better prediction was obtained using a multiple linear model with the droplet size characteristic V_{200} and the droplet velocity characteristic v_{vol10} as predictive variables (R^2 = 0.96).

In conclusion, droplet size as well as droplet velocity characteristics are related with DRP_t and *DPRP*. Because of the strong intercorrelation between droplet size and velocity characteristics for the nozzle-pressure combinations investigated in this study, simple first-order linear regressions with one of the droplet characteristics as a predictor variable, were the best choice to predict DRP_t, $DPRP_{V1}$ and $DPRP_{V2}$. Only in case of $DPRP_H$, both droplet size (V_{200}) as well and droplet velocity (v_{vol10}) were included in a multiple linear regression model. It can be assumed that in cases where droplet velocities and sizes are less correlated (e.g. air assistance or twin fluid nozzles), such an approach - combining droplet velocity and droplet size characteristics - will be necessary to obtain a good prediction of DRP_t and *DPRP*.

Chapter 7 **General conclusions and future work**

7.1. General conclusions

In this dissertation, three different drift assessment means were developed namely PDPA laser measurements, wind tunnel measurements (both indirect drift assessment means) and field drift experiments (direct drift assessment means) to investigate the effect of spray application technique on drift from field sprayers. With these measuring techniques, droplet size and velocity characteristics, drift potential reduction percentages ($DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_{H}$) and drift reduction potentials (DRP_{t}) were determined and compared for different spray application techniques to investigate the effect of nozzle size, nozzle type, spray pressure, boom height, driving speed and air assistance on the amount of near-field sedimenting spray drift and to evaluate the potential of the different measuring techniques. In total, 162 PDPA laser measurements, 51 wind tunnel experiments and 108 field drift experiments were performed. The reference spraying was defined as a standard horizontal spray boom without air support with a spray boom or nozzle height of 0.50 m, a nozzle distance of 0.50 m, ISO 03 standard flat fan nozzles at a pressure of 3.0 bar and a driving speed of 8 km.h^{-1}, typically applying 180 L.ha^{-1} (driving speed and nozzle spacing only applicable for field measurements). This reference spray application was used for a comparative assessment of the different other spray applications.
The main conclusions concerning the drift characteristics of the different spray application techniques and the investigated indirect and direct drift assessment means are listed.

7.1.1. Comparison between the different spray application techniques

- For the different nozzle-pressure combinations, droplet sizes within the spray cloud vary from a few micrometres up to some hundreds of micrometres and droplet velocities from about 0 m.s^{-1} up to 16 m.s^{-1}. Droplet sizes and velocities are related and both are influenced by nozzle type (standard flat fan, low-drift flat fan, air inclusion) as well as nozzle size (ISO 02, 03, 04 and 06) and spray pressure (2.0, 3.0 and 4.0 bar).
- Droplet velocities at a nozzle height of 0.50 m are mainly determined by the ejection velocity at the nozzle exit and by the droplet size. Smaller droplets slow down more rapidly due to the effect of air drag compared to larger droplets which retain their momentum for longer. That is why bigger droplet sizes generally correspond with higher droplet velocities, small droplets with lower droplet velocities. Moreover, droplet velocities for one and the same droplet size range vary depending on nozzle type and size because of variations in ejection velocities.
- Looking at the effect of ***nozzle type***, standard flat fan nozzles produce the finest droplet size spectrum followed by low-drift flat fan nozzles and air injection nozzles for the same nozzle size and spray pressure which is reflected among

others in the proportion of small droplets (V_{100}, V_{200}, etc.). The effect of nozzle type on droplet sizes is more important for smaller ISO nozzle sizes.
For the same droplet size, droplet velocities are the highest for the flat fan nozzles followed by the low-drift nozzles and the air inclusion nozzles. This is caused by the pre-orifice effect in case of a low-drift nozzle and by a combination of Venturi and pre-orifice effect for the air inclusion nozzles resulting in lower ejection velocities for a specific droplet size. In spite of this, droplet velocities are generally the highest for the air inclusion nozzles, followed by the low-drift nozzles and the standard flat fan nozzles - for the same ISO nozzle size and spray pressure - because of their different droplet size characteristics and the fact that larger droplet sizes correspond with higher droplet velocities. Hence, the droplet size effect dominates the ejection velocity effect.
From the wind tunnel and field experiments, it is also found that for the same nozzle size and spray pressure, DRP_t and *DPRP* values are the highest for the air inclusion nozzles followed by the low-drift nozzles and the standard flat fan nozzles and again, the effect of nozzle type is most important for the smaller nozzle sizes.

- The larger the ISO ***nozzle size***, the coarser is the droplet size spectrum and the lower is the proportion of small droplets at a constant pressure. This effect is most pronounced for the standard flat fan nozzles followed by the low-drift flat fan nozzles. For the air inclusion nozzles, the effect of nozzle size on the proportion of small droplets is less important and the proportion of small droplets is low in all the cases.
Moreover, bigger ISO nozzle sizes correspond with higher droplet velocities at a distance of 0.50 m for the same nozzle type and spray pressure. This is caused by two factors which strengthen each other namely, bigger ISO nozzles produce bigger droplets which are in any case faster and droplets of the same size produced by bigger nozzles are faster because of the higher ejection velocities.
These conclusions about the effect of nozzle size on droplet characteristics are clearly reflected in the results from the wind tunnel and the field measurements. The bigger the ISO nozzle size, the higher the *DPRP* and DRP_t values for the standard and the low-drift flat fan nozzles at a constant spray pressure. For the air inclusion nozzles, the effect of nozzle size on *DPRP* and DRP_t values is less clear but in both cases, *DPRP* and DRP_t values are high and the highest values are found for the ISO 03 air inclusion nozzles.
- To investigate the effect of ***spray pressure*** on drift characteristics, a limited series of measurements was carried out with the ISO 03 standard flat fan nozzle within a pressure range from 2.0 to 4.0 bar. For the droplet velocities, only the fastest droplet velocity characteristics (v_{vol75} and v_{vol90}), significantly decrease with decreasing spray pressures. Although decreasing pressure from 3.0 to 2.0 bar did not significantly affect droplet size characteristics, fallout and airborne downwind spray deposits in the wind tunnel significantly increased because of the slight reduction of droplet velocities in combination with a decrease of entrained air velocities. On the other hand, this decrease in spray pressure resulted in a clear decrease in the amounts of field drift which was in contrast with the results from the wind tunnel and the PDPA laser measurements. Increasing the spray pressure from 3.0 to 4.0 bar significantly decreased droplet sizes but the effect was very limited compared to the effect of nozzle size. In the field, an increase in spray drift was found.

- Besides nozzle type, size and spray pressure, all having an effect on spray quality, driving speed and ***spray boom height*** also influence the amount of sedimenting spray drift. Based on the field as well as on the wind tunnel experiments, it was found that operating at a spray boom height as close as possible to the vegetation - without sacrificing the uniformity of the spray pattern - is a good way to reduce drift.
- The effect of ***driving speed*** can only be investigated in a realistic way by means of field drift experiments. In general, a decrease in spray drift is observed for lower driving speeds of 4 and 6 $km.h^{-1}$ while the difference between the reference speed of 8 $km.h^{-1}$ and a speed of 10 $km.h^{-1}$ is statistically non-significant.
- A reducing effect on the total amount of spray drift is demonstrated for the Hardi ISO F 110 02, F 110 03 and LD 110 02 nozzles using ***air assistance*** with drift reduction factors α_d of, respectively, 2.08, 1.77 and 1.53. The use of air assistance has no significant effect for the LD 110 03 nozzles which demonstrates that the finer the spray, the higher the impact of air assistance is on the amount of spray drift.

7.1.2. Evaluation of the indirect and direct drift assessment means

PDPA laser measurements

- The PDPA laser-based measuring set-up is capable of producing huge amounts of useful and repeatable droplet velocity and size information under controlled and repeatable conditions.
- Comparing the results from the PDPA laser measurements with other researches confirms the need for reference nozzles to classify sprays because of the considerable variation of absolute results depending on measuring protocol, settings, type of measuring equipment and variations in reference sprays.

Wind tunnel measurements

- From the three different wind tunnel approaches $DPRP_{V1}$ values are the highest followed by $DPRP_{V2}$ and $DPRP_H$ for the standard flat fan nozzles while for the low-drift nozzles opposite results are found. For the air inclusion nozzles, a relatively good agreement between $DPRP_{V1}$, $DPRP_{V2}$ and $DPRP_H$ values is found.
- Increasing wind tunnel air speed not only increases the magnitude of fallout and airborne spray deposits but also changes the form of the airborne spray profile in a way that the centre of gravity of the moving spray cloud is raised. This change has its effects on *DP* values but *DPRP* values remain fairly constant irrespective of the wind speed conditions for the three different approaches.

Field drift measurements

- Twenty seven drift experiments with the reference spraying indicate the important effect of atmospheric conditions on the amount of near-field sedimenting spray drift. That is why a non-linear drift prediction equation is set up and validated, to predict the expected magnitude of drift for the reference spray application.
- This equation consists of four independent, non-correlated variables namely: drift distance, average wind speed at a height of 3.25 m, average temperature and absolute humidity and shows that decreasing wind speed and temperature and increasing absolute humidity decreases the amount of sedimenting spray drift. In the normal range of weather conditions, the effect of air humidity and temperature

is more important than the effect of wind velocity because of the effect of evaporation which reduces droplet sizes.

- This equation is used to quantify the effect of meteorological conditions on the amount of spray drift and to compare the measurements with the different spraying techniques under different weather conditions to the reference spraying by calculating their drift reduction potential (DRP_t).

General

- A large database with droplet characteristics, wind tunnel fallout and airborne deposits and (absolute) near-field drift results of different spray application techniques is made available together with information about the effects of climatological conditions
- The results of this study are in fairly good agreement with the results from different other studies although it is difficult to compare because of differences in among others spray application techniques, experimental design, tracers, weather and crop conditions. That is why it is increasingly important to unify the different indirect and direct drift assessment means and to put together the different available databases.

7.1.3. Comparison of the indirect and direct drift assessment means

PDPA laser and field measurements

- In general, droplet size as well as droplet velocity characteristics are related with field measurement DRP_t values. DRP_t values increase with increasing values of droplet diameter and droplet velocity characteristics and decrease with increasing percentages of small droplets.
- The proportion of the total volume of droplets smaller than 200 µm in diameter (V_{200}), was found to be the best individual indicator for the amount of sedimenting spray drift in the field with an R^2 of 0.78.
- Besides V_{200}, the droplet size characteristics V_{50}, V_{75}, V_{100}, V_{150} and V_{250} and the velocity span factor (*VSF*) were also strongly related with DRP_t. The higher the *VSF* value, representing a less uniform droplet velocity distribution, the lower the DRP_t value which can be explained by the clear relation between droplet sizes and droplet velocities which is reflected in the *VSF* values.

Wind tunnel and field measurements

- A fairly good correlation between field drift DRP_t and wind tunnel *DPRP* values is found with the best agreement with $DPRP_H$ (R^2 = 0.88) followed by $DPRP_{V2}$ (R^2 = 0.81) and $DPRP_{V1}$ (R^2 = 0.66) which means that the wind tunnel approach calculating the surface under the measured fallout deposit curve, is best suited to represent real near-field sedimenting drift characteristics.
- Similar trends are found - concerning the effect of nozzle type, size, height and pressure - from the *DPRP* and DRP_t results although there are some deviations in absolute results mainly for a varying spray pressure and nozzle height.

PDPA laser and wind tunnel measurements

- The different individual droplet size characteristics are generally best related with $DPRP_H$ followed by $DPRP_{V2}$ and $DPRP_{V1}$ while the opposite was found for the droplet velocity characteristics. With regard to $DPRP_H$, V_{100}, V_{150} and V_{200} have the highest predictive power with an R^2 value of 0.92, while $DPRP_{V1}$ was related most with v_{vol10} ($R^2 = 0.86$) and $DPRP_{V2}$ with *VSF* ($R^2 = 0.90$) which indicates again that droplet sizes and droplet velocities are strongly linked and that droplet size characteristics are more related with fallout deposits compared to airborne deposits while the opposite is found for the droplet velocity characteristics.

General

- Droplet size as well as droplet velocity characteristics are related with DRP_t and *DPRP*.
- The indirect drift assessment method measuring V_{200} values with the PDPA laser is at least as well suited to represent near-field drift characteristics compared with the wind tunnel approach calculating $DPRP_H$ values and even better suited compared with the wind tunnel approaches calculating $DPRP_{V1}$ and $DPRP_{V2}$ values.
- With the PDPA laser, it is only possible to investigate the effect of nozzle type, size and spray pressure whereas the effect of nozzle height can also be investigated by means of wind tunnel measurements. With both indirect techniques, it is difficult to investigate effects like driving speed and air assistance.
- Because of the strong intercorrelation between droplet size and velocity characteristics, first-order linear models with one of the droplet characteristics as a predictor variable were best suited to predict DRP_t, $DPRP_{V1}$ and $DPRP_{V2}$ values respectively based on droplet characteristics V_{200}, v_{vol10} and *VSF*. Only in case of $DPRP_H$, a better prediction was obtained using a multiple linear model with the droplet size characteristic V_{200} and the droplet velocity characteristic v_{vol10} as predictive variables ($R^2 = 0.96$).
- It might be assumed that in cases where droplet velocities and sizes are less correlated (e.g. air assistance or twin fluid nozzles), a combination of droplet velocity and droplet size characteristics will be necessary to come to a good prediction of DRP_t and *DPRP*.
- Field research is appropriate for obtaining realistic estimates of drift under a range of working conditions but field research is time-consuming and expensive. In this study, a measuring protocol and a drift prediction equation were set up to improve the interpretation of field drift data. With this equation and DRP_t of a certain spray application technique, realistic sedimenting field drift data for varying meteorological conditions can be calculated using the drift prediction equation. This information can be used by regulators for decision-making and risk assessment processes taking into account climatological conditions and spray application technique.
- With the indirect drift assessment means (wind tunnel and PDPA laser measurement), driftability experiments can be made with different spraying systems under directly comparable and repeatable conditions and both methods are suited to permit relative studies of drift risk. Moreover, based on $DPRP_H$ or V_{200} - resulting from these indirect drift measurements - the DRP_t of a particular technique can be determined to come to a realistic estimate of field drift data at a driving speed of 8 $km.h^{-1}$ and a boom height of 0.50 m. Hence, with the relatively cheap and easy indirect drift assessment means, it is possible to come to a realistic prediction of drift values which is very useful for all users of plant protection products, constructors and authorities.

7.2. Suggestions for future work

Although this study has shown the drift reduction potential of different spray application techniques and the possibilities of using both indirect and direct drift assessment means, there are still some suggestions for future work within the scope of this research.

Drift reduction techniques

- There are still some new or less popular techniques or nozzle designs which could be tested using the different drift assessment means although a wide range of spray application techniques for field crops has been tested in this study.
- In this study, all field drift experiments were performed on a meadow although crop characteristics can have an effect on drift values as described in section 2.2.6. In 2007-2008, a whole series of field drift experiments will be performed using the reference spraying in different crops (potatoes, cereals, sugar beets, etc.) to quantify the effect of crop characteristics on spray drift.
- In section 5.3.1.2, the effect of spray boom movements on drift values was mentioned. This effect could be investigated in more detail using a demonstration track for field sprayers in combination with an online registration system for boom movements.
- Natural or artificial structures to intercept and retain drift are mostly used and have mainly been studied in orchards. In 2007-2008, wind tunnel and field drift experiments will be performed to investigate the potential of different natural and artificial drift collectors in field crop spraying.
- As described in section 2.2.1.5, there is no consensus about the effect of (drift-reducing) spray application technology on the biological efficacy of plant protection products. At the moment of writing this work, field trials are running to evaluate the biological effect of a selection of the spray application techniques considered in this research. The use of herbicides (sugar beets, chicory, potatoes and maize) as well as fungicides (cereals) is considered. Yield results with the different spray application techniques resulting from these trials in combination with the legislative drift regulations (buffer zones) can be used to perform an economic analysis of the use of drift-reducing spray application techniques.
- This work focuses on spray drift from horizontal boom sprayers. A similar research approach could be followed for orchard sprayers from which it is known that the drift risk is even higher.
- In future, a tool could be developed for a continuous monitoring of the spray drift risk during spray applications combining GIS, meteorological data, product information and spray application parameters. A similar approach was already presented by van de Zande *et al.* (2006).

Drift assessment means

- The 1D PDPA laser-based measuring set-up could be upgraded to obtain additional information about the direction of travel of the spray droplets.
- In this work, the use of air assistance was only studied in the field (Chapter 5). Some preliminary tests were already performed to measure the effect of air assistance on droplet characteristics using the PDPA laser-based measuring set-up. These first tests indicated that the drift-reducing potential of air assistance, can mainly be attributed to a significant increase in droplet velocities (Nuyttens *et al.*, 2007 d). The results of these tests are not discussed in this thesis. In future, extra

tests could be performed and extended to the wind tunnel. These results could be linked with results from the field measurements.

- From the field measurements, a whole dataset of airborne spray drift results is available for the different spray application techniques described in Table 5.1. This data could be processed, evaluated and compared with the sedimenting drift data and with the results from both indirect drift assessment means.

Spray drift modelling

- Measuring results from this study are used as an input, to validate and optimize a CFD drift-prediction model (Baetens *et al*., 2006; 2007 a). This CFD model will be further developed and made available.
- Extra measurements could be performed with the reference spraying to enlarge the database used to set up the statistical drift prediction equation (§ 5.3.1.3) and, if necessary, to optimize this equation.
- Information from this study in combination with the CFD drift-prediction model (Baetens *et al*., 2006; 2007 a) and results from a spray drift risk assessment (De Schampheleire *et al.*, 2006 b), could result in a web-based, user-friendly spray drift risk decision tool which could be consulted by all users of plant protection products and other interested parties like constructors and authorities.

Standardisation and legislation

- (ISO) standards should be further developed at different levels:
  - The drift classification of spraying equipment (ISO/DIS 22369-2, 2007),
  - The measurement and classification of droplet size and velocity spectra of spray nozzles (ISO/CD 25358, 2007),
  - The measurement of drift or drift potential under laboratory conditions (ISO/DIS 22856, 2007).
- Different spray drift studies have already been conducted around the world. The results from these studies should be compiled into a single database to facilitate decision-making and risk assessment processes in the different countries and to harmonize drift mitigation strategies on an international level.

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Appendices

Annex 1: PDPA laser measuring volume calculation

Using the fringe model, it is possible to obtain expressions for some of the properties of the measuring volume defined by the intersection of the laser beams. The beam waist diameter d_w (m) of the focused laser beam is expressed by:

$$d_w = \frac{4}{\pi}.\frac{f.\lambda}{d_e} \text{ and } d_e = E.d_u$$

where d_u = beam waist diameter of the unfocused laser beam (m),
d_e = expanded beam waist diameter of the unfocused laser beam (m),
E = beam expansion ratio (-),
f = focal length of the transmitter lens (m),
λ = laser light wavelength (m).

For our set-up d_u= 1.40 mm; E= 0.5; f = 500 mm and λ = 514.5 nm or d_w= 0.468 mm
The measuring volume parameters are (Figure I):

$$w = \frac{d_w}{\cos\left(\frac{\theta}{2}\right)} \quad \text{and} \quad l = \frac{d_w}{\sin\left(\frac{\theta}{2}\right)}$$

where w = width of the measuring volume (m),
l = length of the measuring volume (m),
θ = angle between laser beams (°).

For a beam separation D_b of 10 mm and a focal length of 500 mm, θ is equal to 1.146°. This gives w = 0.468 mm and l = 46.8 mm.
The number of fringes N_f for this optical set-up is 18 and can be calculated by:

$$N_f = \frac{4}{\pi}.\frac{D_b}{d_e}$$

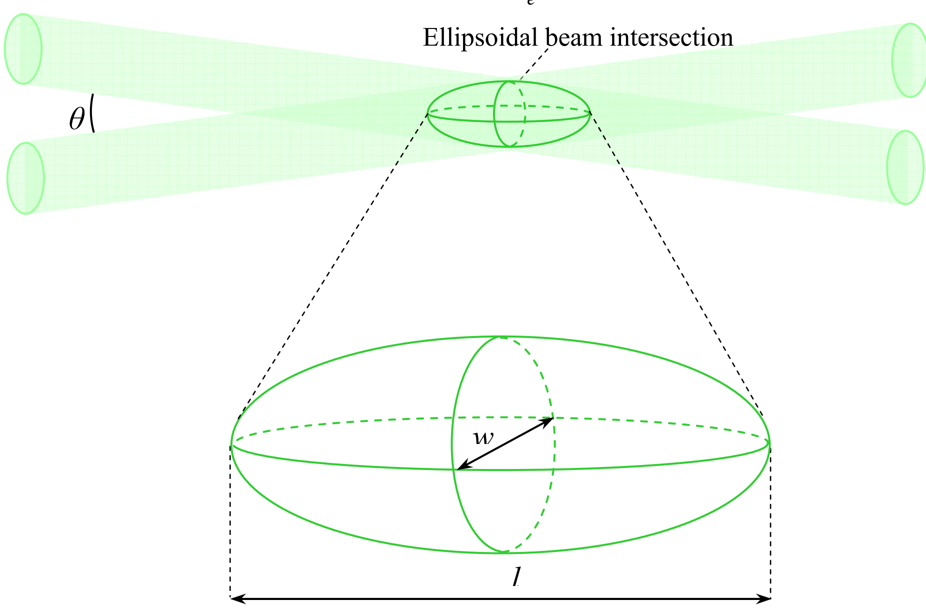


Figure I: Dimensions of the ellipsoidal PDPA laser measuring volume

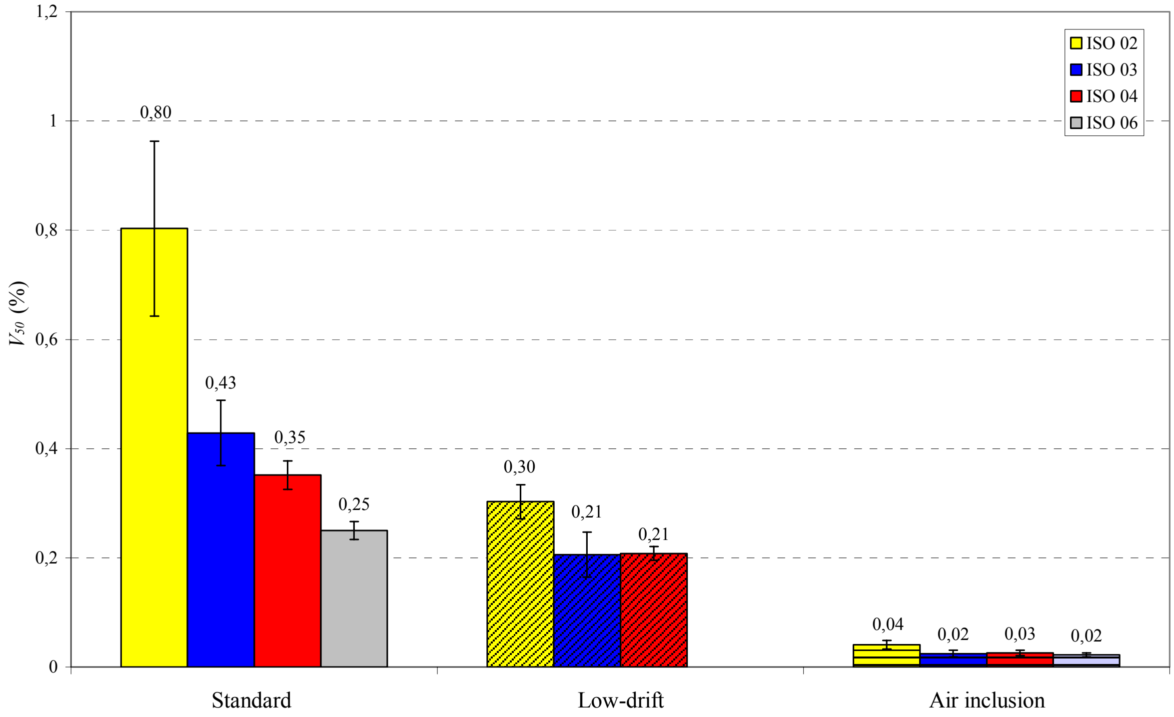
Annex 2: Accredited flow rate measurements of the different test nozzles at a pressure of 3.0 bar

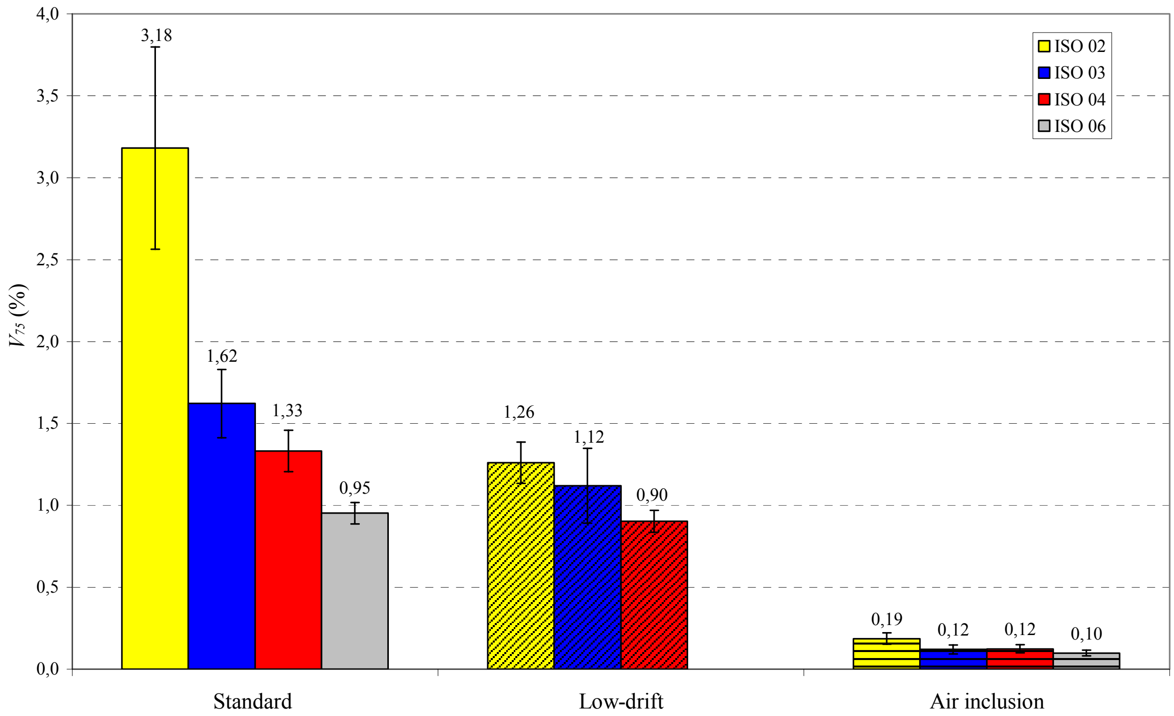
Nozzle	Nominal flow rate at 3.0 bar (L.min^{-1})	Nozzle 1 Average (L.min^{-1})	Nozzle 1 Deviation of nominal flow rate (%)	Nozzle 2 Average (L.min^{-1})	Nozzle 2 Deviation of nominal flow rate (%)	Nozzle 3 Average (L.min^{-1})	Nozzle 3 Deviation of nominal flow rate (%)	Nozzle 4 Average (L.min^{-1})	Nozzle 4 Deviation of nominal flow rate (%)	Nozzle 5 Average (L.min^{-1})	Nozzle 5 Deviation of nominal flow rate (%)	Water temperature (°C)	Ambient temperature (°C)	Relative humidity (%)
Delavan LF 110 01*	0.39	0.40	2.72	0.38	-1.76	0.39	0.12	0.38	-2.02	0.40	2.21	23.4	24.0	61
Lurmark F 110 03*	1.20	1.19	-0.87	1.15	-3.75	1.23	2.80	1.21	1.02	1.23	2.77	22.0	22.3	47
Lechler LU 120 06*	2.32	2.25	-2.86	2.35	1.38	2.32	-0.05	2.31	-0.54	2.37	2.31	23.0	23.8	43
TeeJet 80 08*	2.58$^{\$}$	2.59	0.39	2.57	-0.27	2.58	0.03	2.61	1.23	2.58	0.18	17.4	17.0	49
TeeJet 80 15*	5.92	5.91	-0.15	5.96	0.74	5.99	1.14	5.97	0.79	5.92	0.04	22.6	21.0	52
Hardi ISO F 110 02	0.80	0.79	-0.97	0.81	0.93	0.80	-0.27	0.81	0.97	0.80	0.54	16.3	16.0	50
Hardi ISO F 110 03	1.20	1.24	3.66	1.18	-1.36	1.20	0.30	1.24	3.66	1.19	-1.25	20.8	21.0	56
Hardi ISO F 110 04	1.60	1.62	0.95	1.60	-0.04	1.58	-1.06	1.62	1.08	1.62	1.41	17.1	18.3	52
Hardi ISO F 110 06	2.40	2.44	1.81	2.45	2.15	2.43	1.38	2.46	2.33	2.43	1.44	18.2	18.0	51
Hardi ISO LD 110 02	0.80	0.79	-1.09	0.78	-2.44	0.78	-1.89	0.79	-0.81	0.78	-2.49	16.3	16.0	50
Hardi ISO LD 110 03	1.20	1.18	-1.67	1.24	3.33	1.21	0.83	1.23	2.50	1.23	2.50	16.9	17.2	50
Hardi ISO LD 110 04	1.60	1.61	0.61	1.62	1.01	1.60	0.25	1.60	0.25	1.60	0.21	17.1	18.3	52
Hardi ISO Injet 110 02	0.80	0.76	-5.22	0.79	-0.81	0.76	-4.57	0.79	-0.94	0.77	-4.24	18.2	18.0	49
Hardi ISO Injet 110 03	1.20	1.17	-2.50	1.21	0.83	1.23	2.50	1.18	-1.67	1.19	-0.83	18.1	18.5	50
Hardi ISO Injet 110 04	1.60	1.53	-4.53	1.56	-2.26	1.56	-2.41	1.57	-1.76	1.57	-1.80	18.2	18.0	50
Hardi ISO Injet 110 06	2.40	2.21	-7.87	2.32	-3.48	2.28	-5.10	2.30	-4.18	2.26	-5.66	17.5	19.0	53

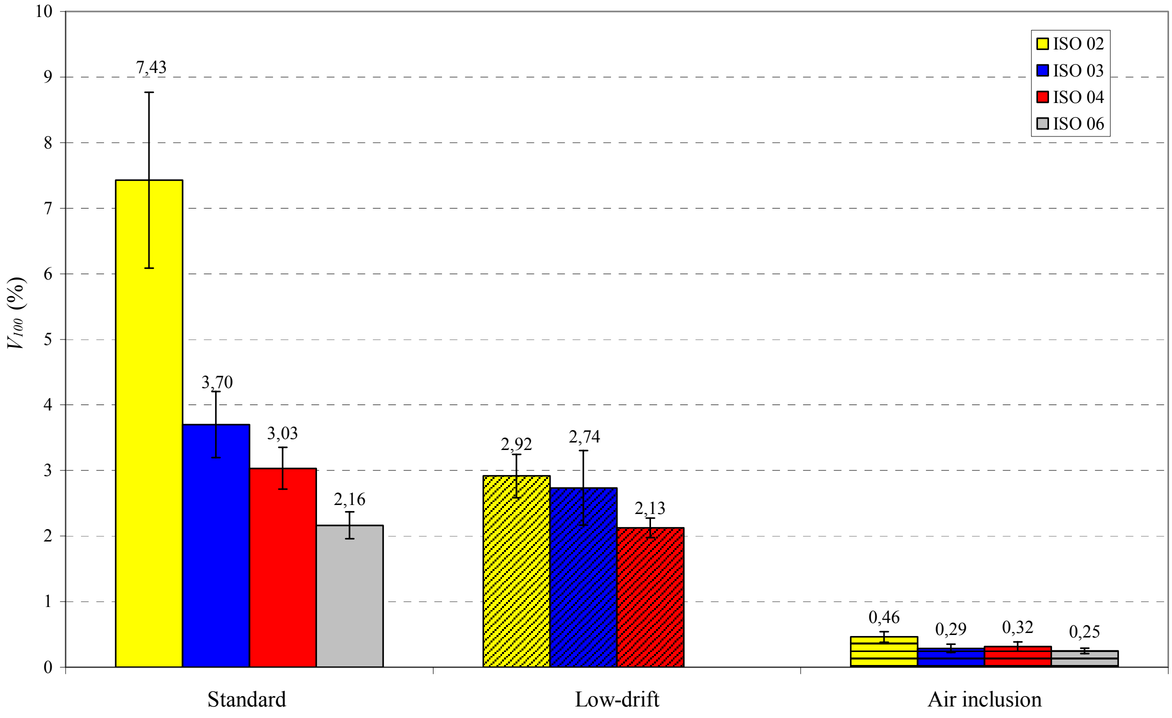
* BCPC reference nozzle-pressure combinations; $ measurements carried out at a pressure of 2.0 bar

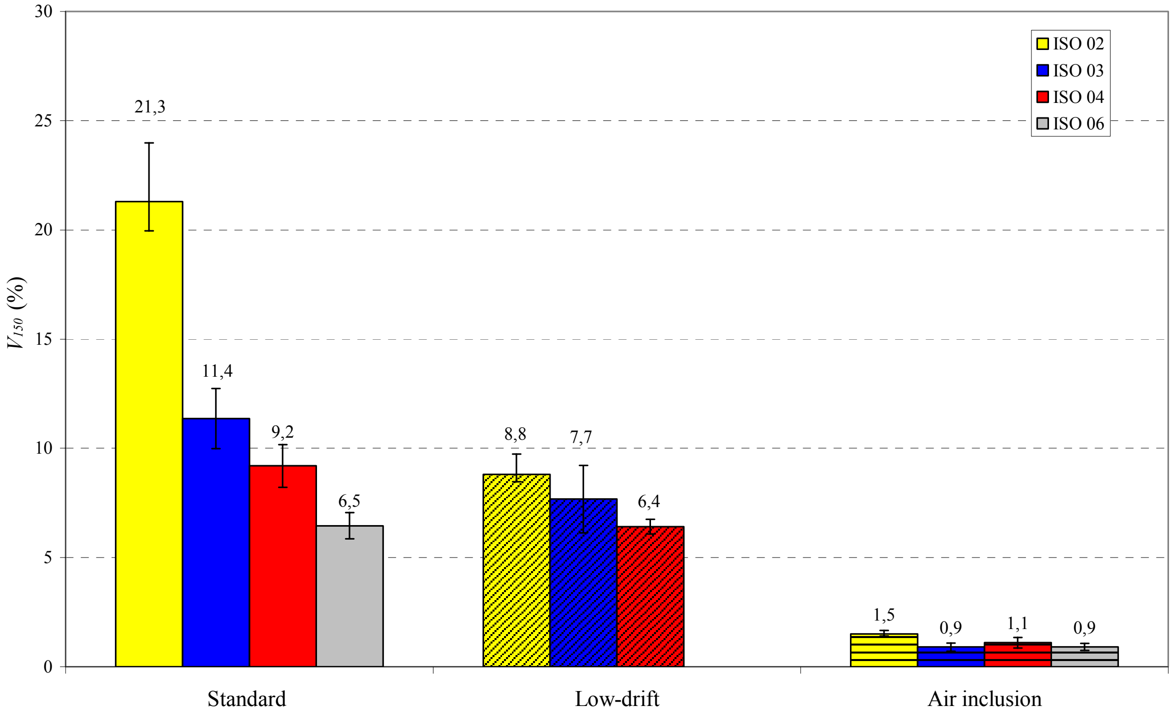
Selected nozzles

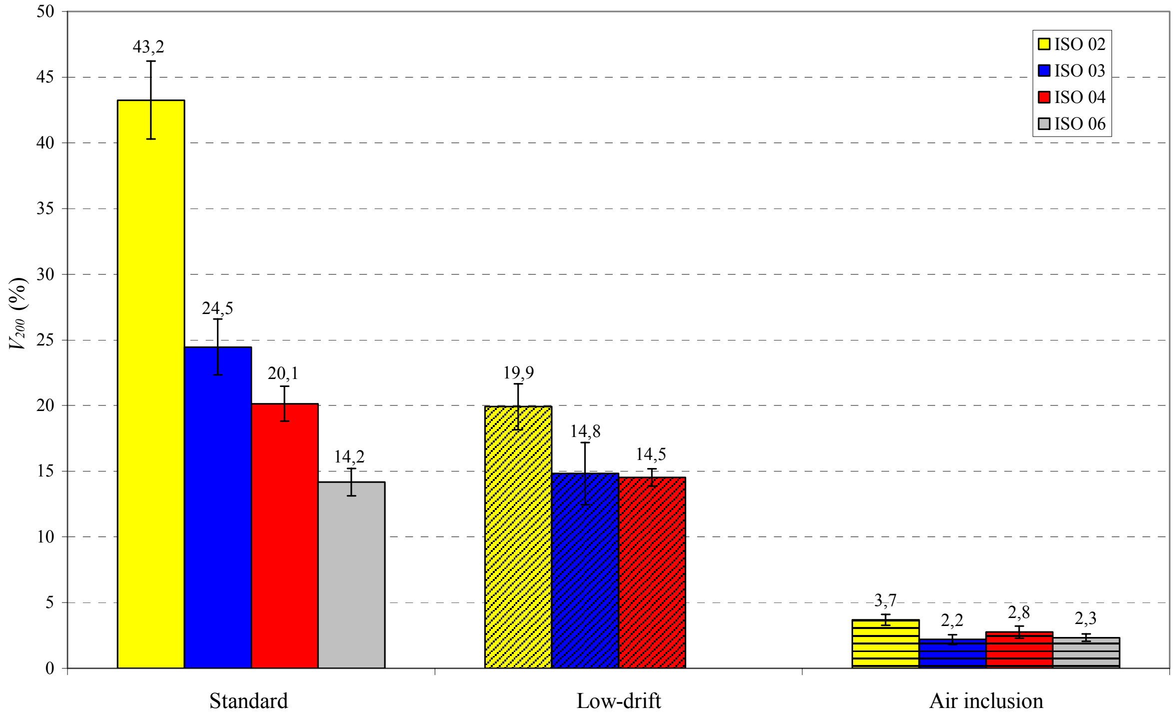
Annex 3: Proportion of total volume in % of droplets smaller than 50, 75, 100, 150, 200 and 250 µm in diameter (V_{50}, V_{75}, V_{100}, V_{150}, V_{200}, V_{250}) for the different Hardi nozzle types at a pressure of 3.0 bar together with the 95% confidence intervals



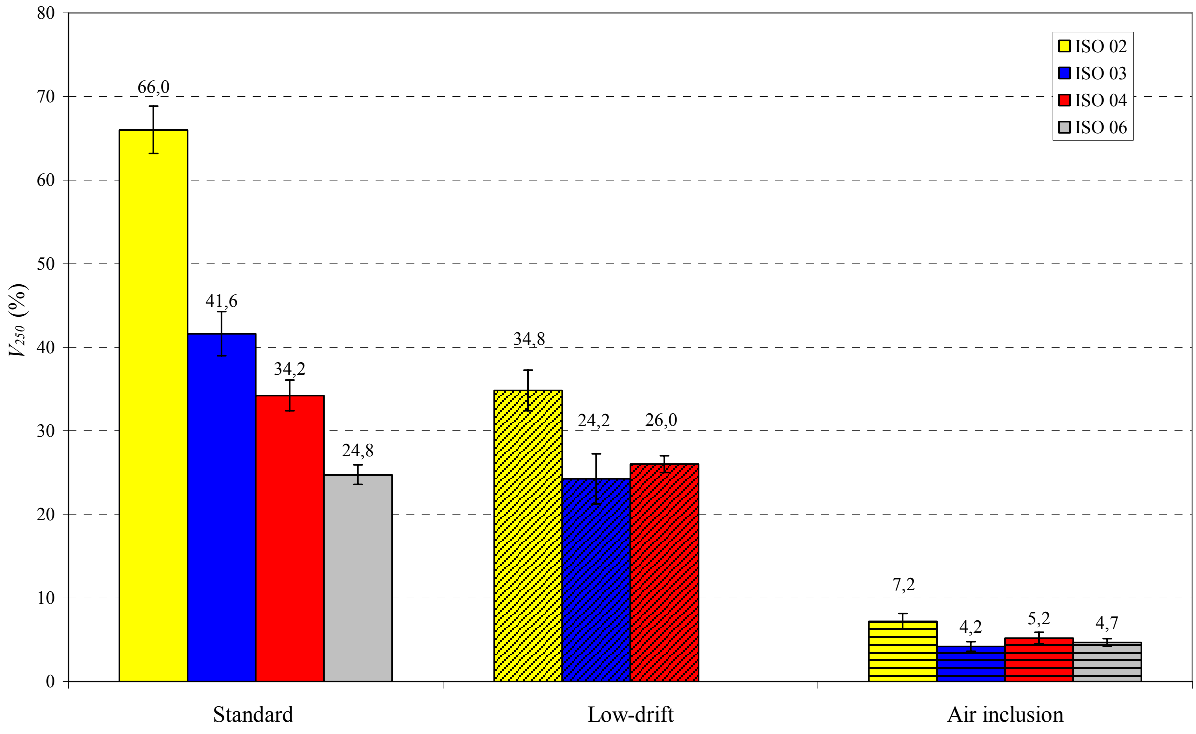



10
9
8
7
6
5
4
3
2
1
0
V100 (%)
7,43
3,70
3,03
2,16
2,92
2,74
2,13
0,46
0,29
0,32
0,25
Standard
Low-drift
Air inclusion
ISO 02
ISO 03
ISO 04
ISO 06


30
25
20
15
10
5
0
V150 (%)
21,3
11,4
9,2
6,5
8,8
7,7
6,4
1,5
0,9
1,1
0,9
Standard
Low-drift
Air inclusion
ISO 02
ISO 03
ISO 04
ISO 06

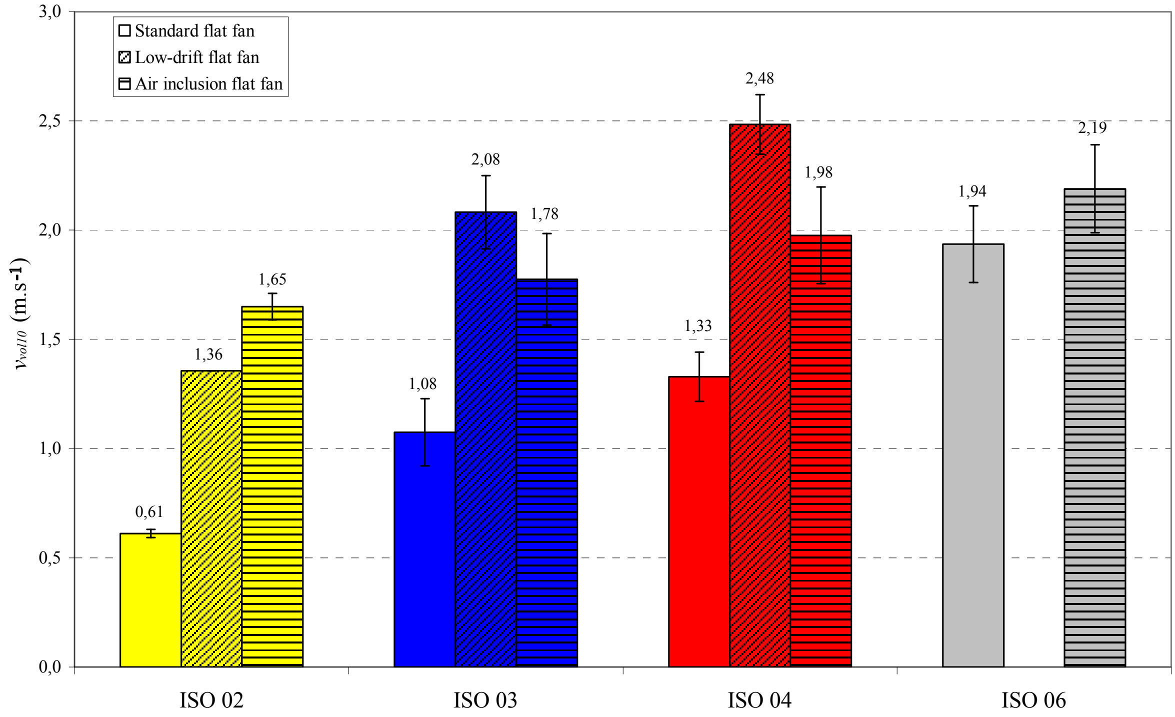


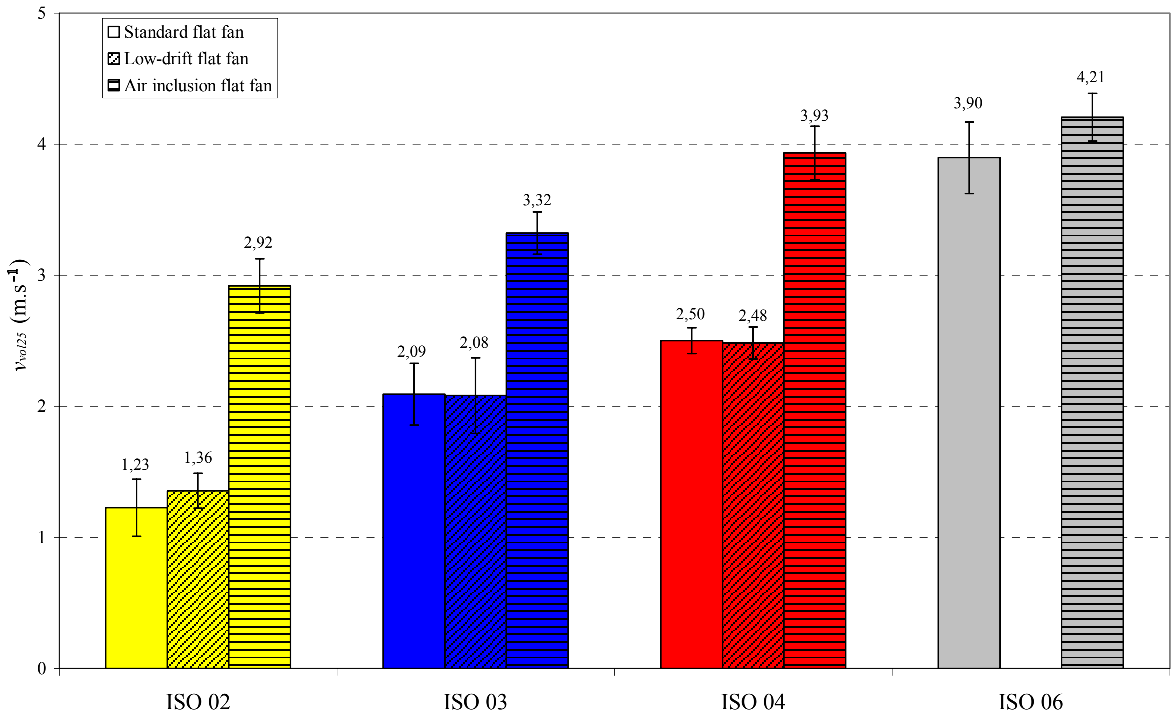
50
45
40
35
30
25
20
15
10
5
0
V_{200} (%)
43,2
24,5
20,1
14,2
19,9
14,8
14,5
3,7
2,2
2,8
2,3
ISO 02
ISO 03
ISO 04
ISO 06
Standard
Low-drift
Air inclusion

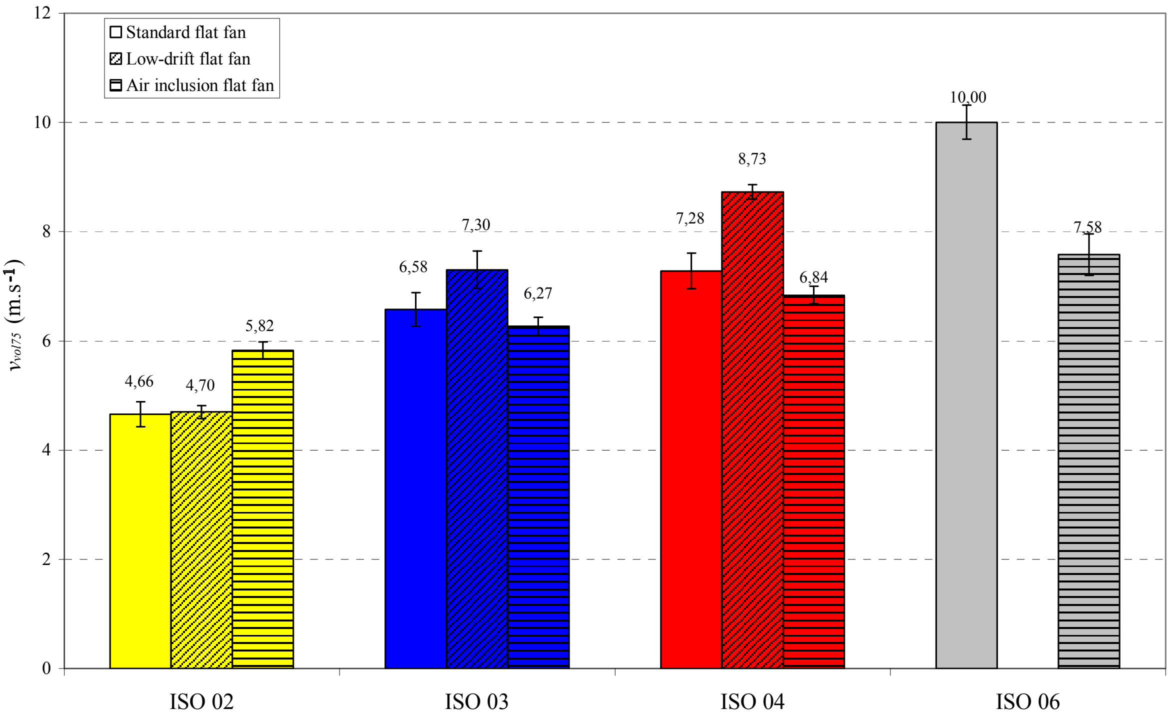


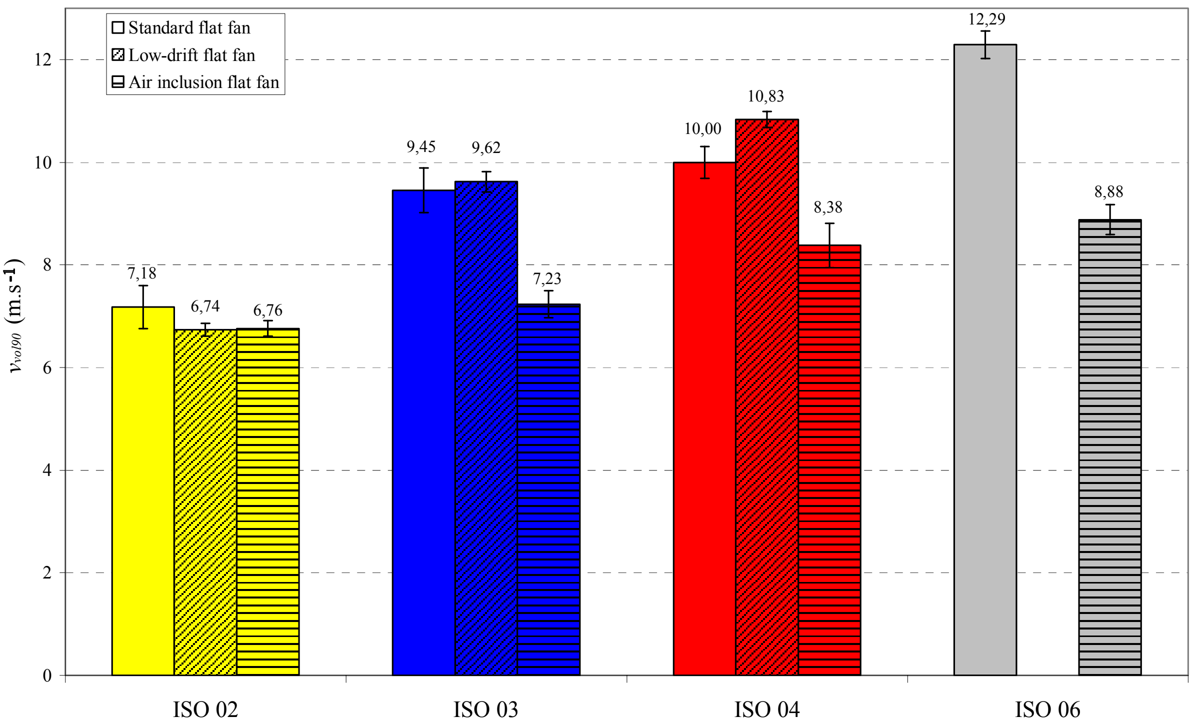
80
70
60
50
40
30
20
10
0
V_{250} (%)
66,0
41,6
34,2
24,8
34,8
24,2
26,0
7,2
4,2
5,2
4,7
ISO 02
ISO 03
ISO 04
ISO 06
Standard
Low-drift
Air inclusion

Annex 4: Droplet velocities below which slower droplets constitute 10, 25, 75 and 90% of the total volume (v_{vol10}, v_{vol25}, v_{vol75} and v_{vol90}) for different Hardi nozzles at a pressure of 3.0 bar together with the 95% confidence intervals

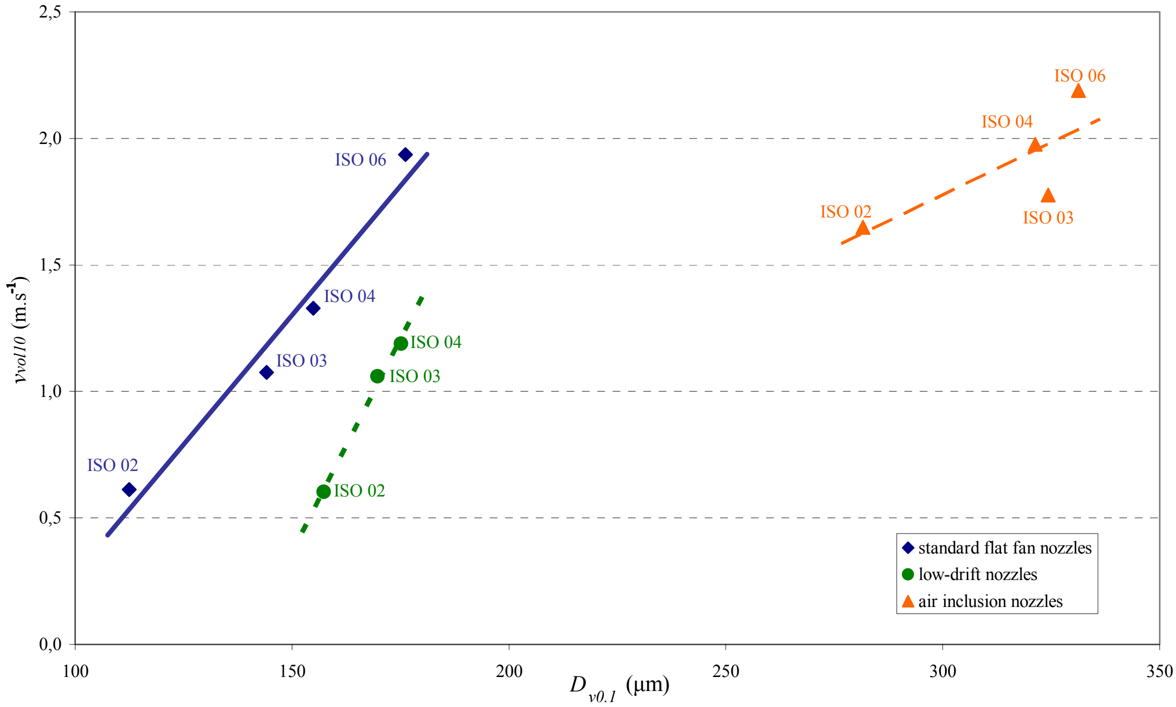


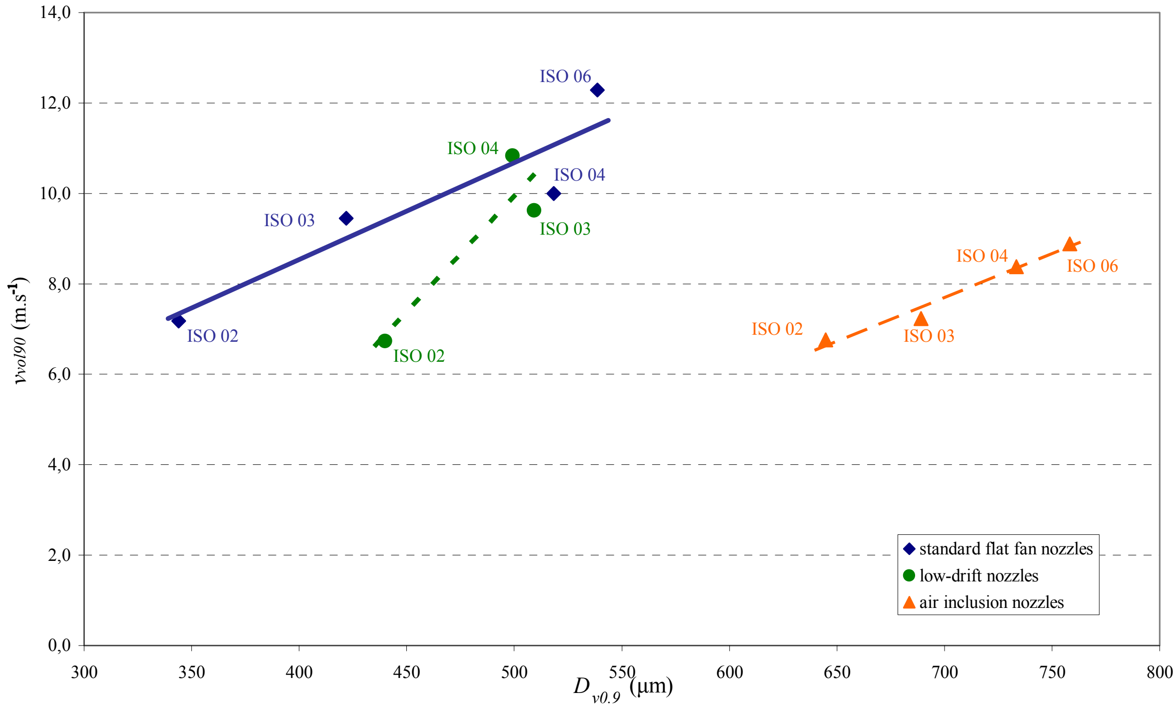



Standard flat fan
Low-drift flat fan
Air inclusion flat fan
v_{vol75} (m.s-1)
0
2
4
6
8
10
12
4,66
4,70
5,82
6,58
7,30
6,27
7,28
8,73
6,84
10,00
7,58
ISO 02
ISO 03
ISO 04
ISO 06

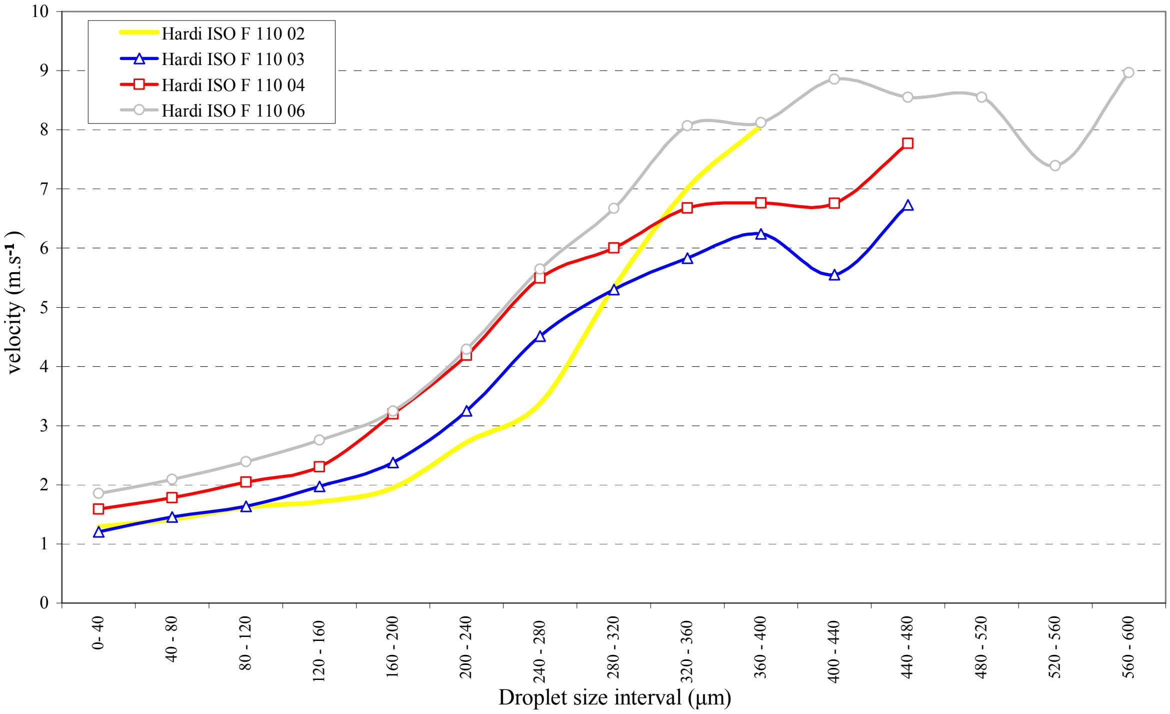

Standard flat fan
Low-drift flat fan
Air inclusion flat fan
v_{vol90} (m.s-1)
0
2
4
6
8
10
12
7,18
6,74
6,76
9,45
9,62
7,23
10,00
10,83
8,38
12,29
8,88
ISO 02
ISO 03
ISO 04
ISO 06

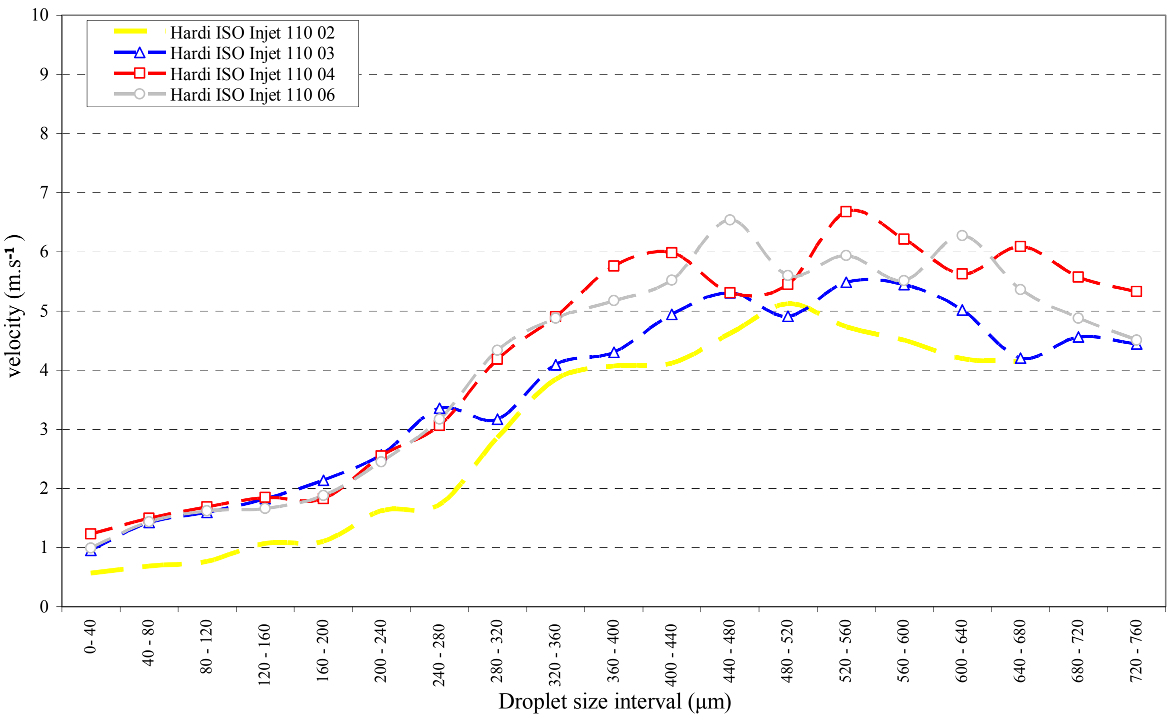
Annex 5: Droplet velocities below which slower droplets constitute 10 and 90% of the total volume (v_{vol10}, v_{vol90}) in relation to volume diameters below which smaller droplets constitute 10 and 90% of the total spray volume ($D_{v0.1}$, $D_{v0.9}$) for different Hardi nozzles at a pressure of 3.0 bar





Annex 6: Average droplet velocities for the different droplet size classes of different ISO sizes of Hardi ISO F standard nozzles and Hardi ISO Injet air inclusion nozzles at a pressure of 3.0 bar





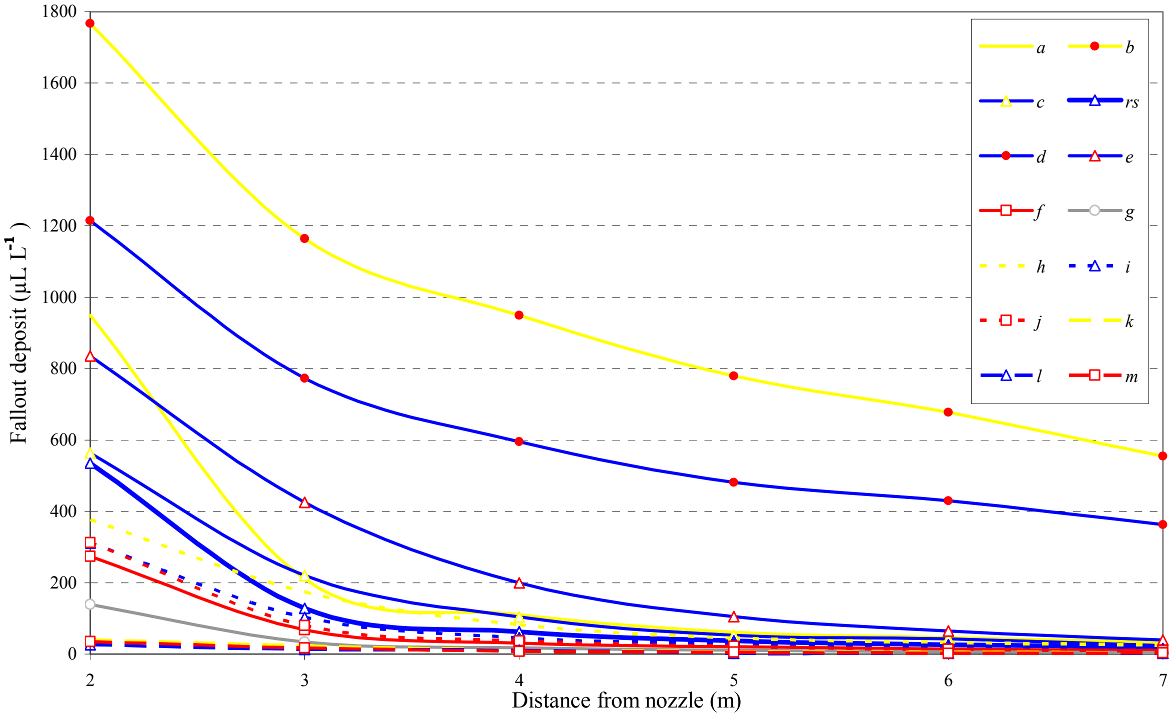
Annex 7: Fallout and airborne deposit results of the 51 wind tunnel experiments

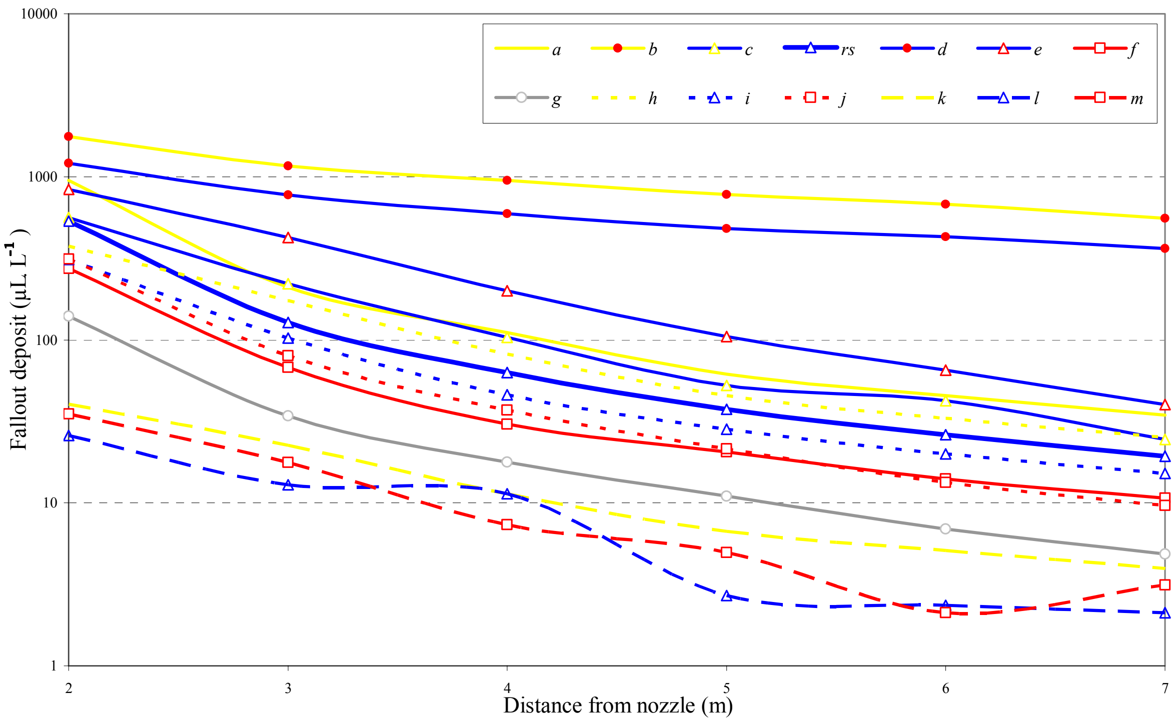
Nozzle	Pressure (bar)	Nozzle height (m)	Flow rate[b] (L.min^{-1})	Wind speed (m.s^{-1})	Number of repetitions	V_5	V_4	V_3	V_2	V_1=H_1	H_2	H_3	H_4	H_5	H_6
F 110 02	3.0	0.50	0.80	2	1	5.9	6.6	16.2	179.9	948.8	210.8	110.9	61.7	45.5	34.5
F 110 02	3.0	0.50	0.80	5	1	247.5	777.7	1319.7	1645.8	1767.0	1164.0	948.8	779.9	677.8	555.2
F 110 03	2.0	0.50	0.98	2	7	2.4	4.2	76.7	463.6	585.5	238.4	96.0	52.5	35.6	21.7
						0.0	0.0	42.9	279.8	558.9	191.1	97.6	40.5	49.4	22.6
						1.9	6.2	87.2	413.2	546.2	232.6	117.5	64.9	42.1	29.1
F110 03[a]	3.0	0.50	1.20	2	24	2.1	2.1	13.9	168.2	585.0	127.9	62.4	33.0	21.7	17.0
						2.1	2.1	12.9	149.6	604.1	107.8	51.6	33.5	22.7	18.1
						1.5	2.0	8.0	113.4	599.5	138.8	59.2	32.8	24.4	16.9
						2.0	1.5	9.1	149.6	665.0	141.6	74.6	43.3	27.7	20.2
						1.6	2.6	17.6	178.4	510.5	142.8	79.7	48.6	28.4	20.2
						2.0	3.0	9.0	101.8	594.0	118.3	57.4	34.9	24.5	16.5
						0.0	0.0	3.4	84.9	433.1	102.6	57.0	31.4	24.1	14.7
						0.0	1.5	16.4	186.5	416.6	138.2	68.8	45.2	29.3	16.4
						5.0	5.0	10.0	99.7	488.4	124.6	59.8	39.9	29.9	29.9
						5.1	5.1	15.3	203.6	585.2	157.8	81.4	40.7	30.5	25.4
						0.0	0.0	15.1	126.2	494.5	126.2	60.6	35.3	25.2	20.2
						0.0	0.0	15.0	140.2	440.7	135.2	65.1	40.1	25.0	15.0
						0.0	0.0	5.0	55.4	332.2	100.7	50.3	30.2	25.2	20.1
						8.6	7.3	23.2	92.2	555.9	110.8	55.0	35.0	27.3	18.2
						12.3	10.0	41.3	303.0	505.5	174.4	90.4	59.5	36.3	28.6
						1.5	1.5	16.7	146.8	553.2	112.8	49.8	27.6	22.7	12.3
						3.4	0.0	7.9	105.9	421.2	106.4	52.2	30.5	22.7	20.7
						1.5	0.5	20.7	228.4	852.1	140.7	58.5	34.3	22.7	16.6
F110 03[a]	3.0	0.50	1.20	5	1	118.7	519.2	810.3	1179.3	1214.3	772.4	595.1	481.8	429.6	362.6
F110 03	3.0	0.70	1.20	2	1	not applicable				835	425	200	105	65	40
F 110 04	3.0	0.50	1.60	2	7	1.1	1.5	3.0	43.3	253.3	60.4	31.1	22.8	14.4	11.0
						0.0	0.0	0.0	33.5	266.1	62.2	25.3	14.5	11.2	8.9
						0.0	0.0	1.5	51.6	301.1	80.3	34.6	24.3	16.6	12.2
F 110 06	3.0	0.50	2.40	2	4	1.3	3.6	10.9	34.6	180.2	39.9	20.1	12.5	8.1	6.1
						0.0	0.0	1.0	23.3	98.4	28.4	15.5	9.6	5.7	3.6

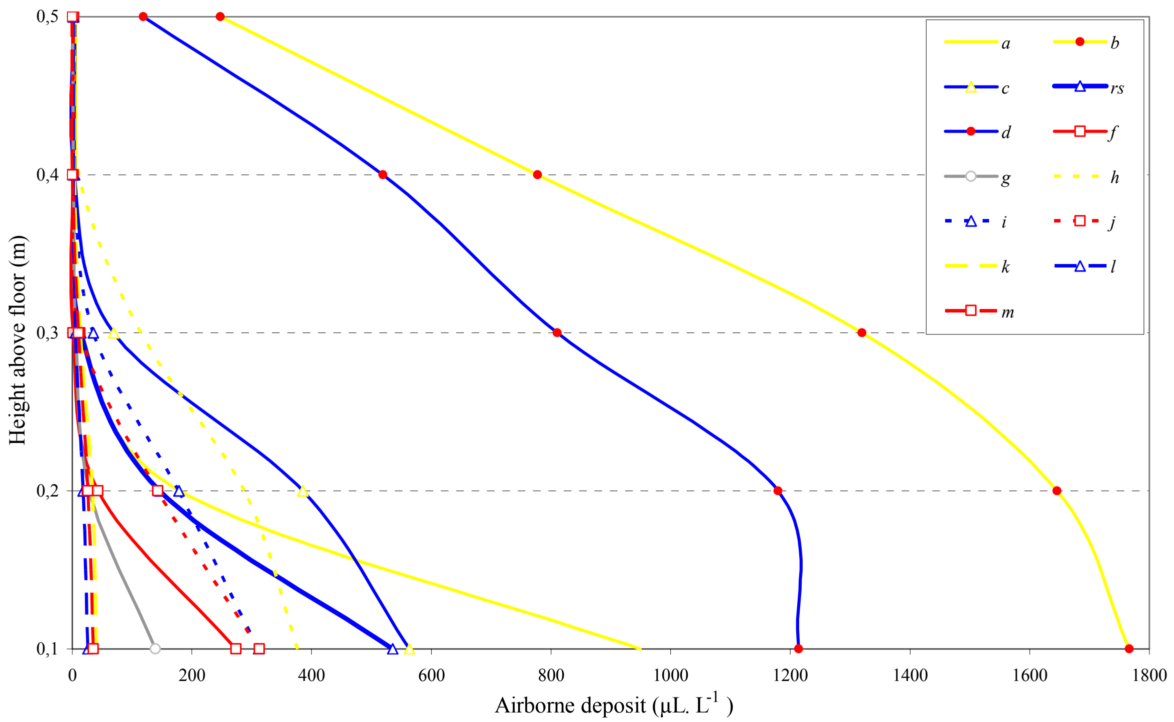
Nozzle	Pressure (bar)	Nozzle height (m)	Flow rate[b] (L.min^{-1})	Wind speed (m.s^{-1})	Number of repetitions	V_5	V_4	V_3	V_2	V_1=H_1	H_2	H_3	H_4	H_5	H_6
LD 110 02	3.0	0.50	0.80	2	8	1.1	7.5	104.2	270.2	350.2	154.0	69.4	34.0	23.4	18.9
						2.3	9.2	98.2	275.4	353.7	158.1	67.5	35.3	21.5	18.4
						0.0	5.2	109.9	265.1	346.8	149.3	70.5	32.7	25.2	18.6
						13.7	22.8	148.1	342.5	455.7	233.9	119.2	79.7	62.3	44.8
LD 110 03	3.0	0.50	1.20	2	5	0.5	2.6	36.8	187.6	342.9	114.5	46.0	26.1	17.9	13.3
						0.0	0.0	48.7	229.2	334.7	110.4	44.0	29.5	21.2	17.1
						6.0	10.0	19.5	117.3	257.6	82.9	47.9	29.5	21.0	15.0
LD 110 04	3.0	0.50	1.60	2	5	2.7	3.4	20.8	244.3	424.2	109.8	42.8	23.1	15.9	10.2
						0.4	0.0	6.1	82.2	227.9	62.0	27.0	16.7	11.0	8.0
						4.7	2.0	11.4	103.1	286.6	68.5	41.7	24.4	13.0	10.6
Injet 110 02	3.0	0.50	0.80	2	5	1.1	1.2	11.9	25.5	30.5	15.9	7.8	4.4	2.9	1.9
						0.9	0.9	10.1	32.7	44.3	24.2	10.9	6.0	3.4	2.5
						3.8	7.7	23.0	42.1	49.8	26.8	15.3	15.3	11.5	7.7
						7.7	7.7	15.4	38.6	46.3	23.1	15.4	7.7	7.7	7.7
						0.0	0.0	7.6	30.3	30.3	22.7	7.6	0.0	0.0	0.0
Injet 110 03	3.0	0.50	1.20	2	3	0.2	0.3	6.0	18.1	26.2	13.1	5.0	2.9	1.9	1.1
						5.2	5.2	10.4	20.8	31.2	15.6	10.4	5.2	5.2	5.2
						0.0	0.0	0.0	15.2	20.3	10.1	0.0	0.0	0.0	0.0
Injet 110 04	3.0	0.50	1.60	2	3	0.1	0.2	4.5	21.0	32.0	14.4	6.5	3.3	2.5	1.7
						0.0	0.0	19.5	31.2	39.0	19.5	11.7	7.8	3.9	3.9
						0.0	0.0	7.7	26.8	34.5	19.2	3.8	3.8	0.0	3.8

[a] Reference spray application; F, Hardi ISO 110 standard flat fan nozzles; LD, Hardi ISO 110 low-drift nozzles; Injet, Hardi ISO Injet air inclusion nozzles

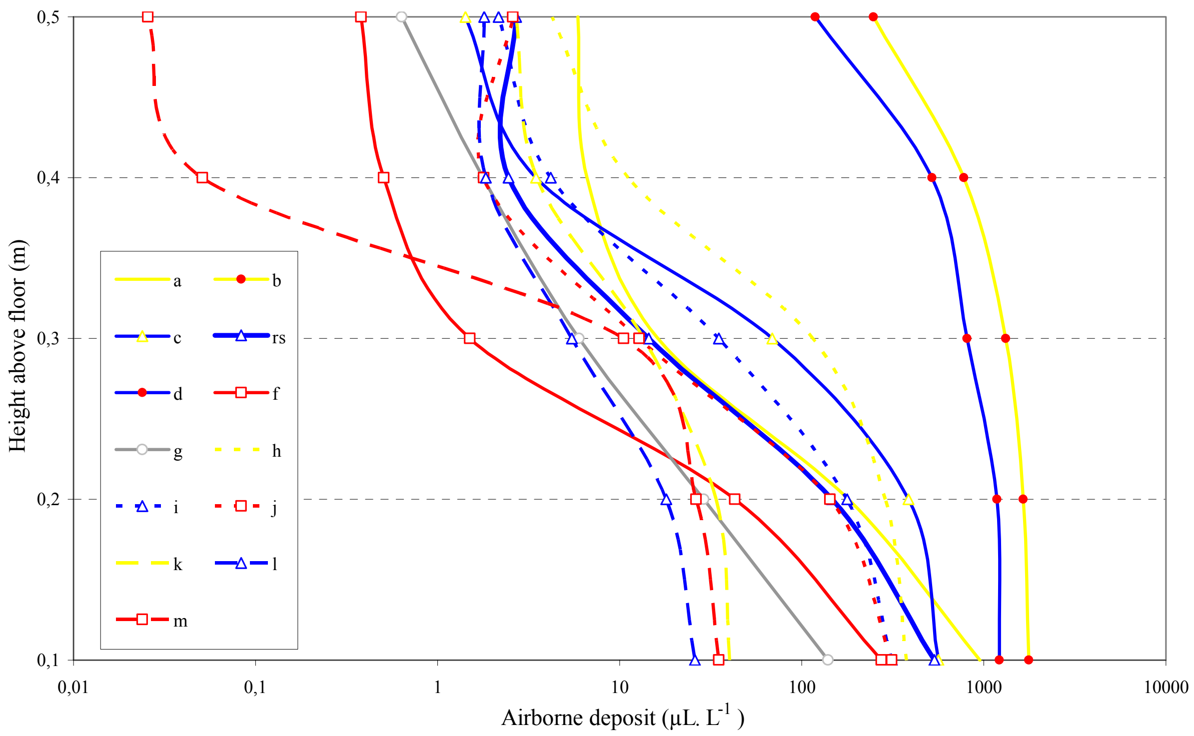
Annex 8: Average fallout and airborne deposit results of the 14 spray applications (*a* - *m* and *rs*) tested in the wind tunnel and described in Table 5.1 both with a linear and a logarithmic scale of the deposit axis





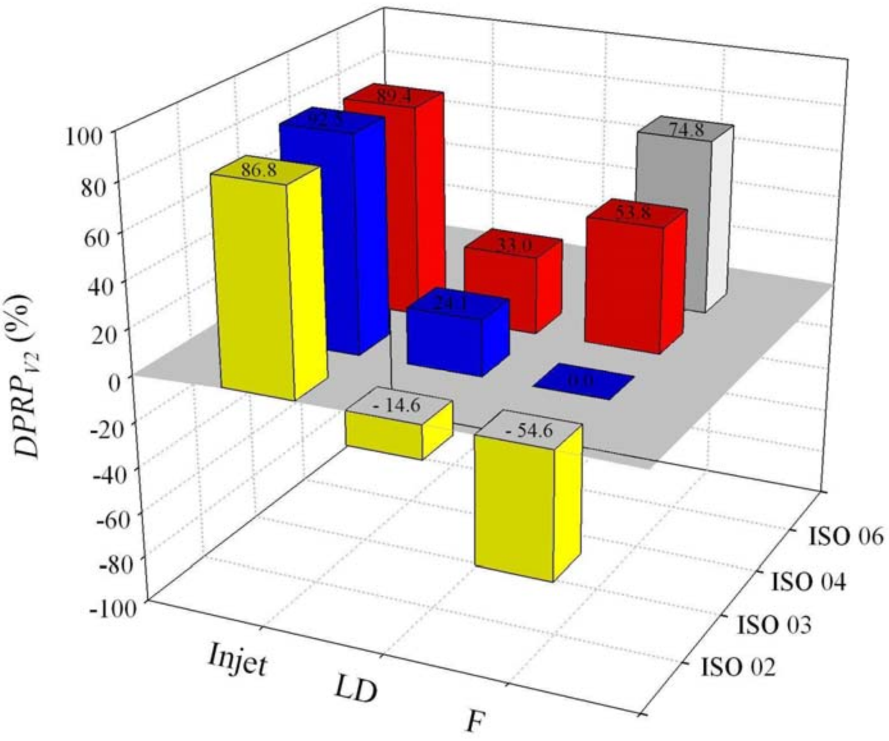


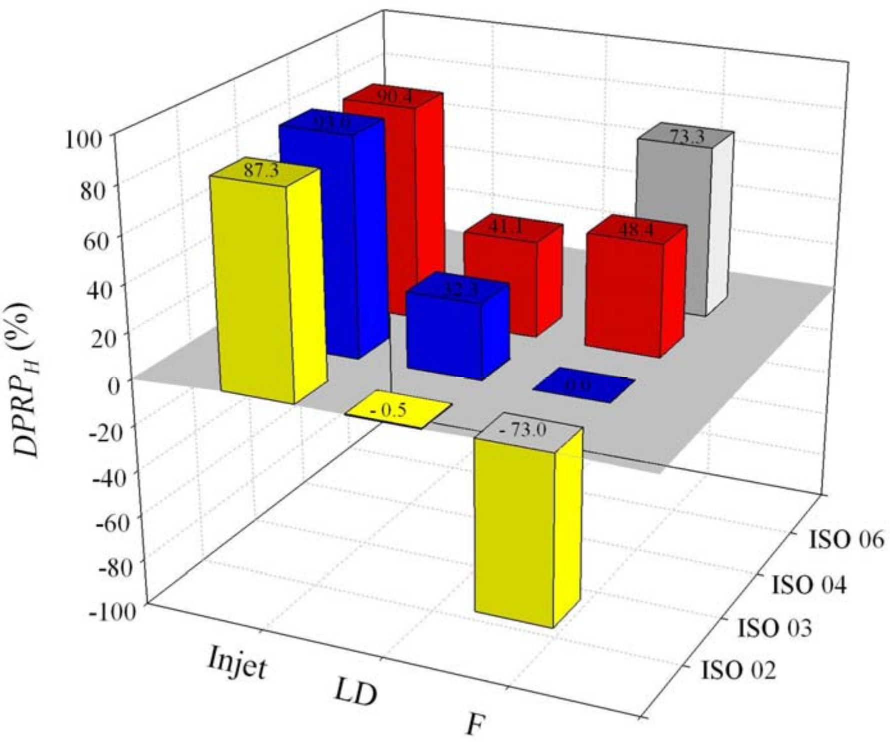
Height above floor (m)
Airborne deposit (µL. L-1)
0,5
0,4
0,3
0,2
0,1
0
200
400
600
800
1000
1200
1400
1600
1800
a
b
c
rs
d
f
g
h
i
j
k
l
m



Height above floor (m)
Airborne deposit (µL. L-1)
0,5
0,4
0,3
0,2
0,1
0,01
0,1
1
10
100
1000
10000
a
b
c
rs
d
f
g
h
i
j
k
l
m

Annex 9: *DPRP$_{V2}$* and *DPRP$_H$* values for different ISO sizes (02, 03, 04 and 06) of Hardi standard flat fan (F), low-drift (LD) and air inclusion nozzles (Injet) at a spray pressure of 3.0 bar



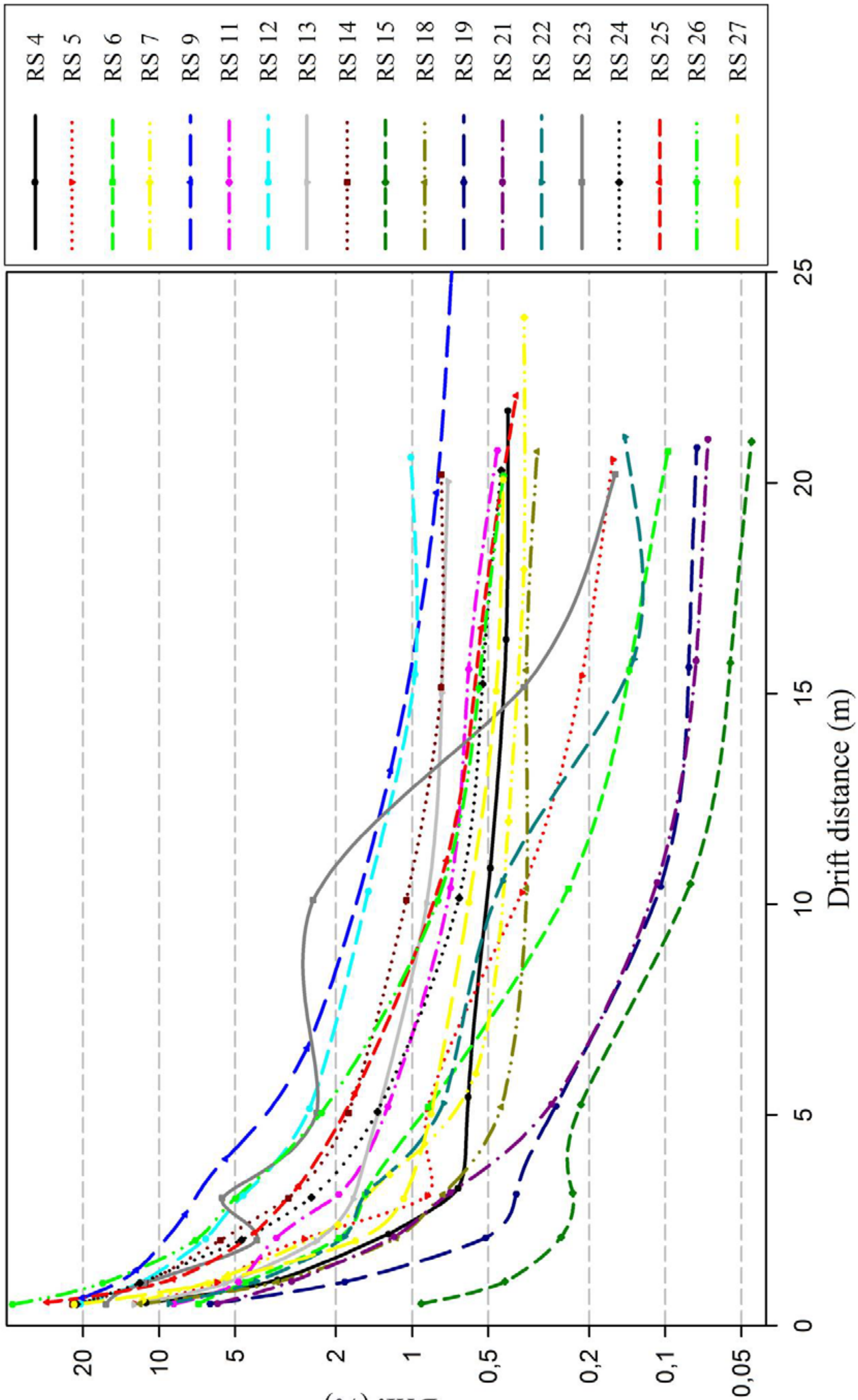


Annex 10: Recoveries (*Rc*, %) expressing the ratio between the measured tracer deposit and the amount of applied tracer for the different field drift experiments

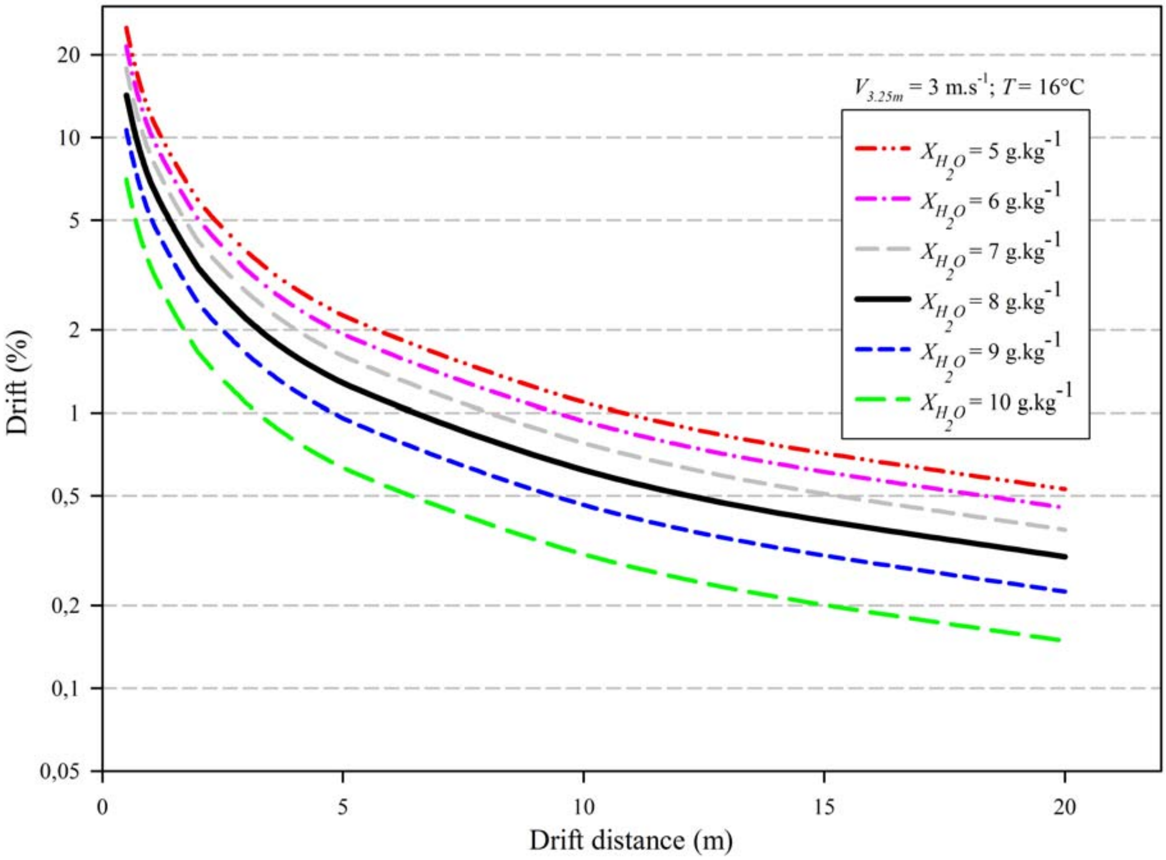
Experiment	*Rc* (%)	Experiment	*Rc* (%)	Experiment)	*Rc* (%)	Experiment)	*Rc* (%)
RS 1	100$	A 1	75	I 2	81	O 2	62
RS 2	100$	A 2	78	I 3	84	O 3	82
RS 3	100$	A 3	54	J 1	78	P 1	76
RS 4	87	B 1	72	J 2	89	P 2	78
RS 5	90	B 2	66	J 3	90	P 3	93
RS 6	77	B 3	74	K 1	69	P 4	80
RS 7	81	C 1	86	K 2	71	Q 1	90
RS 8	73	C 2	75	K 3	53	Q 2	77
RS 9	72	C 3	71	K 4	79	Q 3	88
RS 10	78	D 1	100$	K 5	78	Q 4	82
RS 11	80	D 2	92	K 6	82	Q 5	85
RS 12	82	D 3	78	L 1	74	R 1	82
RS 13	89	E 1	100$	L 2	30*	R 2	81
RS 14	80	E 2	87	L 3	67	R 3	85
RS 15	98	E 3	100$	L 4	60	S 1	100$
RS 16	80	F 1	81	L 5	78	S 2	79
RS 17	90	F 2	100$	L 6	83	S 3	100$
RS 18	71	F 3	99	M 1	71	S 4	79
RS 19	75	F 4	54	M 2	72	S 5	74
RS 20	74	G 1	78	M 3	41*	T 1	81
RS 21	76	G 2	80	M 4	88	T 2	78
RS 22	60	G 3	76	M 5	97	T 3	80
RS 23	56	H 1	81	N 1	66	RS_v 1	82
RS 24	76	H 2	83	N 2	66	RS_v 2	78
RS 25	98	H 3	79	N 3	58	RS_v 3	68
RS 26	86	H 4	78	N 4	77	RS_v 4	89
RS 27	79	I 1	85	O 1	35*	RS_v 5	73

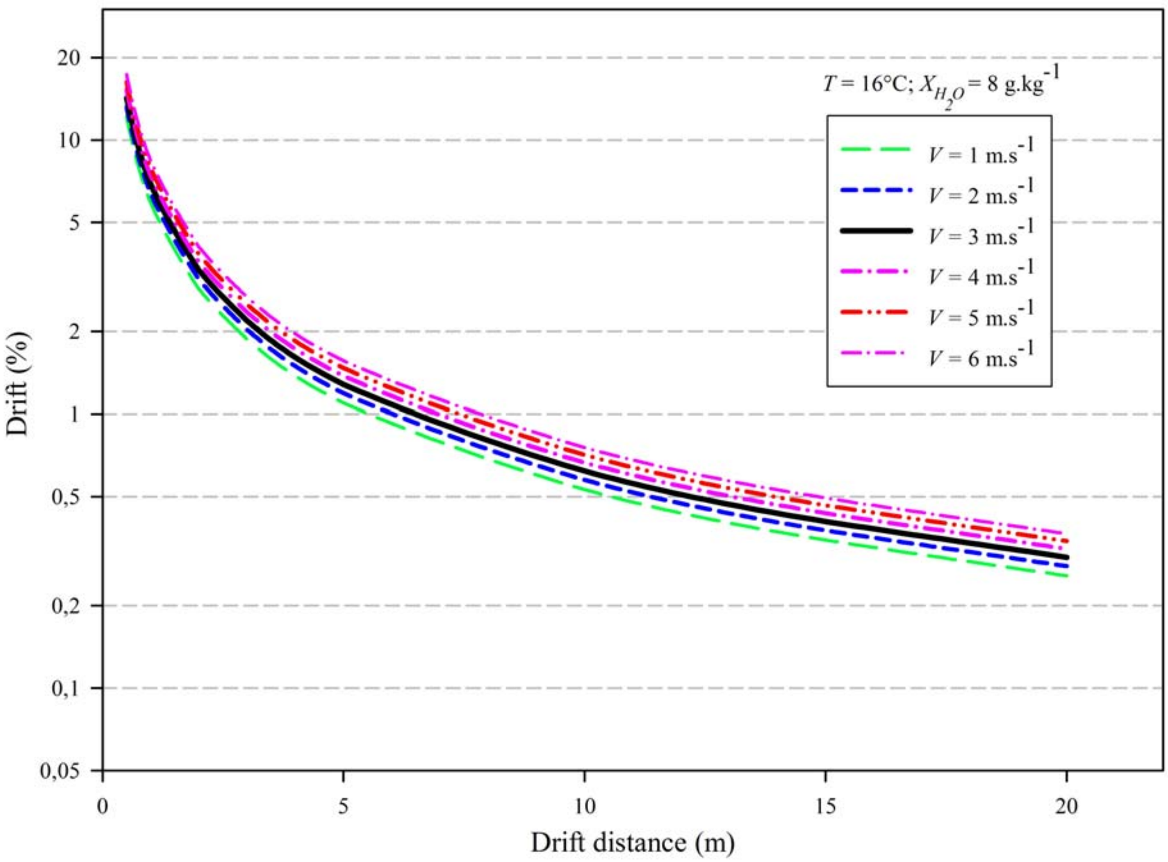
$ Measured *Rc* > 100%, *Rc* set as 100%;
* outlier replaced by the average *Rc* of the corresponding measuring session

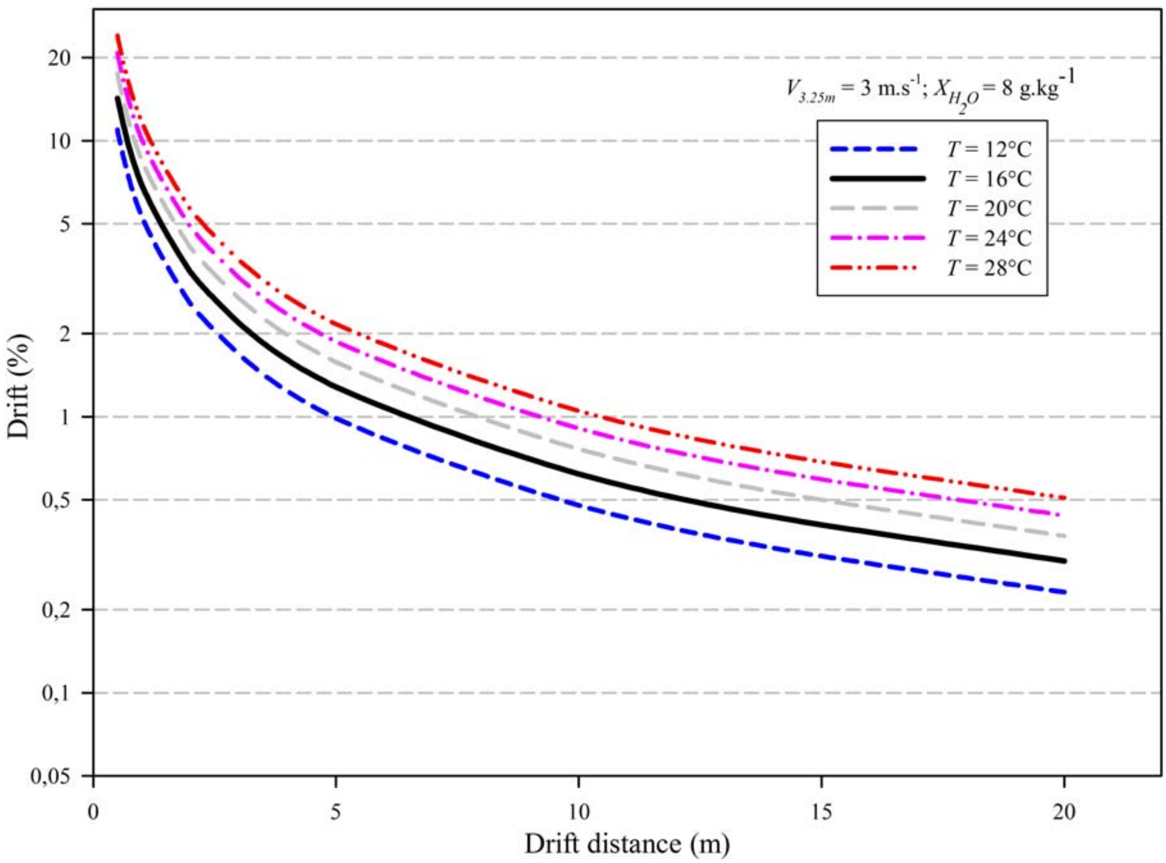
Annex 11: Average sedimenting drift data of the three sampling lines for the different reference sprayings (RS)



Annex 12: Predicted drift curves for the reference spraying on a meadow under different climatological conditions illustrating the effect of absolute humidity (X_{H_2O}), wind velocities at a height of 3.25 m ($V_{3.25m}$) and average temperature (T)

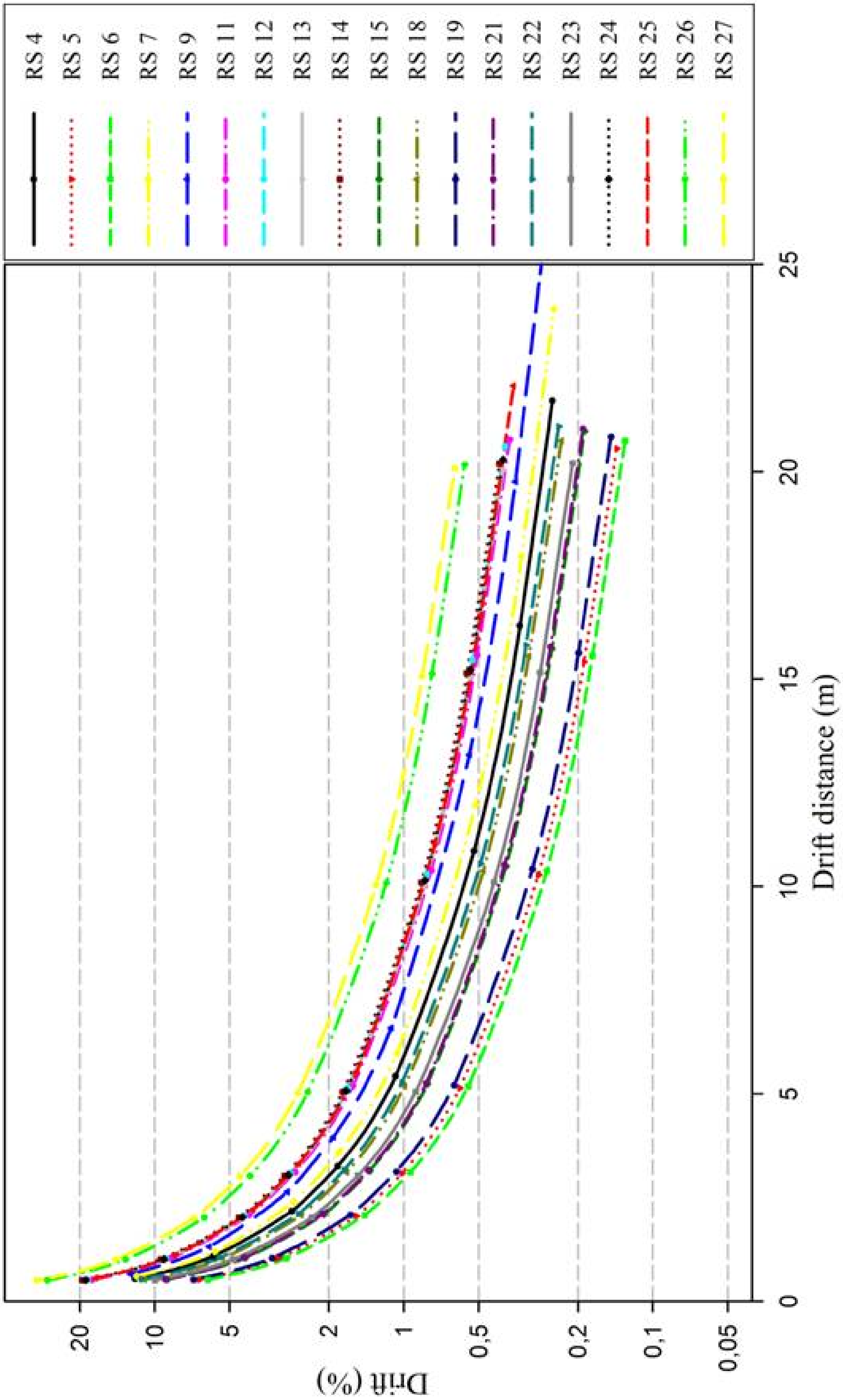






$V_{3.25m}$ = 3 m.s^{-1}; X_{H_2O} = 8 g.kg^{-1}
T = 12°C
T = 16°C
T = 20°C
T = 24°C
T = 28°C
Drift (%)
20
10
5
2
1
0,5
0,2
0,1
0,05
0
5
10
15
20
Drift distance (m)

Annex 13: Predicted sedimenting drift curves for the weather conditions corresponding with the different reference sprayings (RS)



Annex 14: Overview of the meteorological variables for the other sprayings

Experiment	*RH* (%)	X_{H_2O} (g.kg^{-1})	*T* (°C)	$V_{1.50m}$ (m.s^{-1})	$V_{3.25m}$ (m.s^{-1})	*V* (m.s^{-1})	*δ* (°)	*A.S.* (°C.m^{-1})	T_d (°C)
A 1	66.4	10.0	20.5	5.62	4.17	4.90	17.3	0.32	14.0
A 2	69.9	10.4	20.3	3.66	2.82	3.24	0.5	0.29	14.7
A 3	66.5	9.9	20.4	5.18	3.95	4.57	15.1	0.24	13.9
B 1	87.8	9.8	15.7	5.48	4.63	5.06	27.5	0.28	13.7
B 2	83.9	10.5	17.5	4.17	3.13	3.65	10.8	0.40	14.7
B 3	80.0	9.7	17.0	4.20	3.29	3.75	6.1	0.27	13.5
C 1	86.9	10.7	17.3	2.55	1.88	2.22	16.2	0.31	15.1
C 2	86.6	10.6	17.4	4.37	3.50	3.94	7.3	0.44	15.2
C 3	76.6	10.0	18.2	4.16	3.38	3.77	18.8	0.33	14.0
D 1	83.5	9.9	16.7	2.89	3.67	3.28	14.8	-0.20	13.9
D 2	75.6	9.4	17.5	3.98	4.79	4.39	4.5	-0.28	13.2
D 3	87.5	6.4	9.4	1.64	1.99	1.81	20.0	-0.37	7.5
E 1	66.8	8.7	19.0	4.01	5.05	4.53	2.2	-0.18	12.6
E 2	63.9	9.8	20.8	3.68	4.90	4.29	32.6	-0.37	13.7
E 3	63.2	9.3	20.2	4.05	5.31	4.68	20.2	-0.27	13.0
F 1	63.0	6.5	14.6	0.84	1.10	0.97	74.3	-0.22	7.6
F 2	54.2	5.8	15.3	2.79	3.10	2.94	32.5	-0.36	6.1
F 3	90.8	7.1	10.4	3.12	3.37	3.25	32.2	-0.22	9.0
F 4	59.7	7.0	16.6	1.73	1.97	1.85	3.3	-0.24	8.7
G 1	55.5	6.1	15.6	2.09	2.80	2.44	20.8	-0.36	6.7
G 2	57.6	6.0	14.7	1.52	1.65	1.58	35.2	-0.31	6.5
G 3	89.6	7.2	10.8	4.23	5.03	4.63	48.2	-0.27	9.2
H 1	52.1	5.5	15.0	2.67	3.31	2.99	93.5	-0.22	5.3
H 2	56.1	5.8	14.7	3.26	3.82	3.54	12.5	-0.30	6.0
H 3	87.9	7.2	11.1	3.41	4.04	3.72	39.8	-0.21	9.1
H 4	62.0	7.2	16.4	2.12	2.49	2.31	22.8	-0.24	9.1
I 1	73.6	9.8	18.5	2.87	3.62	3.24	26.7	-0.40	13.7
I 2	71.6	9.9	19.1	3.48	3.80	3.64	20.2	-0.49	13.9
I 3	68.8	10.3	20.5	2.55	3.07	2.81	34.0	-0.48	14.5
J 1	90.9	9.4	14.6	3.81	3.04	3.43	25.2	0.22	13.1
J 2	88.8	9.4	14.9	3.81	2.98	3.40	4.1	0.20	13.1
J 3	88.2	9.4	15.0	3.64	2.88	3.26	18.0	0.20	13.1
K 1	68.4	8.5	17.9	3.45	3.90	3.68	45.3	-0.43	12.0
K 2	64.4	7.8	17.1	2.15	3.01	2.58	57.6	-0.21	10.3
K 3	68.2	8.3	17.1	3.01	3.68	3.35	64.2	-0.29	11.2
K 4	63.7	6.4	14.2	4.79	5.83	5.31	16.2	-0.36	7.4
K 5	65.6	6.1	13.0	4.01	4.86	4.43	35.3	-0.39	6.7
K 6	57.8	6.0	14.6	2.92	3.33	3.12	2.7	-0.48	6.4
L 1	62.0	8.6	19.1	1.10	1.25	1.18	65.6	-0.49	11.7
L 2	63.9	8.4	18.4	4.54	4.54	4.54	36.5	-0.36	11.4
L 3	48.2	8.5	23.2	3.70	4.19	3.95	34.4	-0.21	11.6
L 4	87.4	7.3	11.3	3.38	4.07	3.73	50.7	-0.25	9.3
L 5	77.2	9.4	17.1	2.20	2.60	2.40	32.7	-0.37	13.1
L 6	76.8	8.0	14.7	2.40	2.65	2.52	8.3	-0.50	10.6

Experiment	*RH* (%)	X_{H_2O} (g.kg^{-1})	*T* (°C)	$V_{1.50m}$ (m.s^{-1})	$V_{3.25m}$ (m.s^{-1})	*V* (m.s^{-1})	*δ* (°)	*A.S.* (°C.m^{-1})	T_d (°C)
M 1	61.1	8.7	19.7	1.14	1.30	1.22	94.6	-0.27	11.9
M 2	60.0	8.5	19.5	3.73	4.51	4.12	41.5	-0.46	11.5
M 3	46.4	8.4	23.5	3.34	3.83	3.59	36.9	-0.40	11.3
M 4	85.6	7.3	11.7	3.83	4.27	4.05	29.1	-0.25	9.3
M 5	73.5	8.3	16.1	2.43	2.89	2.66	0.9	-0.53	11.3
N 1	70.3	8.4	16.8	3.36	3.61	3.49	28.3	-0.44	11.4
N 2	49.9	8.4	22.4	4.23	4.87	4.55	24.8	-0.44	11.4
N 3	41.8	7.7	24.0	5.16	5.83	5.50	41.7	-0.37	10.2
N 4	74.6	8.2	15.5	3.10	3.58	3.34	8.5	-0.53	11.0
O 1	61.7	9.6	21.0	2.06	2.52	2.29	12.0	-0.42	13.4
O 2	60.6	12.7	25.9	4.18	5.04	4.61	28.5	-0.50	17.7
O 3	65.5	6.2	13.3	1.52	1.54	1.53	16.2	-0.37	7.0
P 1	61.7	12.1	24.8	2.57	3.30	2.94	31.6	-0.56	16.9
P 2	70.2	6.4	12.8	0.90	1.65	1.27	96.3	-0.38	7.5
P 3	53.0	5.4	14.5	2.97	3.92	3.44	10.3	-0.29	5.0
P 4	80.4	9.1	16.0	2.91	3.41	3.16	10.5	-0.31	12.7
Q 1	68.0	10.4	20.8	3.07	3.64	3.35	25.2	-0.48	14.7
Q 2	65.8	10.5	21.4	1.66	1.91	1.78	18.8	-0.42	14.7
Q 3	62.8	10.6	22.4	3.12	3.36	3.24	11.7	-0.59	15.0
Q 4	64.5	11.3	22.9	1.63	1.97	1.80	19.8	-0.59	15.9
Q 5	63.0	12.0	24.3	2.06	2.36	2.21	34.6	-0.66	16.8
R 1	61.8	4.6	9.8	4.05	4.46	4.26	9.2	-0.38	2.8
R 2	57.5	4.6	10.8	3.21	4.05	3.63	22.2	-0.44	2.8
R 3	37.8	3.6	13.5	2.51	2.66	2.59	17.5	-0.56	-0.6
S 1	56.5	12.2	26.4	1.61	2.49	2.05	70.4	-0.88	17.1
S 2	43.4	11.6	30.2	2.04	3.14	2.59	42.1	-0.79	16.3
S 3	41.9	11.4	30.4	2.20	3.91	3.05	28.2	-0.76	16.0
S 4	82.7	8.2	14.0	2.52	3.08	2.80	33.7	-0.53	11.1
S 5	62.1	7.4	16.8	3.09	3.68	3.38	12.7	-0.39	9.5
T 1	86.0	6.5	9.8	1.99	2.60	2.29	22.6	-0.34	7.6
T 2	67.3	4.2	7.3	1.72	1.85	1.79	20.8	-0.27	1.6
T 3	65.9	4.5	8.4	1.92	2.25	2.08	21.8	-0.40	2.4
Minimum	**37.8**	**3.6**	**7.3**	**0.84**	**1.10**	**0.97**	**0.5**	**-0.88**	**-0.59**
Average	**67.9**	**8.4**	**17.2**	**3.06**	**3.37**	**3.22**	**28.3**	**-0.28**	**10.87**
Maximum	**90.9**	**12.7**	**30.4**	**5.62**	**5.83**	**5.50**	**96.3**	**0.44**	**17.67**

RH, average relative humidity; X_{H_2O}, absolute humidity; *T*, average temperature; $V_{1.50m}$, average wind speed at 1.50 m; $V_{3.25m}$, average wind speed at 3.25 m; *V*, average wind speed; *δ*, deviation of ideal driving direction; *A.S.*, atmospheric stability; T_d, dew-point temperature

Annex 15: Sedimenting drift data of the 65 successful other sprayings (A-T)

	A 1				A 2				A 3			
Collector distance (m)	Drift distance (m)	Drift (%) Line A	Line B	Line C	Drift distance (m)	Drift (%) Line A	Line B	Line C	Drift distance (m)	Drift (%) Line A	Line B	Line C
0.5	0.5	43.8	21.7	18.8	0.5	11.8	4.8	16.6	0.5	50.4	53.0	12.3
1	1.0	33.7	23.0	10.6	1.0	3.3	5.9	7.1	1.0	39.1	28.7	0.6
2	2.1	17.8	10.7	0.2	2.0	3.1	0.7	2.4	2.1	9.8	1.2	0.8
3	3.1	10.5	3.9	2.7	3.0	2.3	2.6	4.4	3.1	0.7	2.9	0.7
5	5.2	0.7	4.0	3.2	5.0	0.9	1.0	3.1	5.2	4.7	1.5	0.8
10	10.5	3.7	1.8	1.9	10.0	0.7	0.4	0.6	10.4	0.9	0.7	0.7
15	15.7	0.7	0.7	0.4	15.0	0.3	0.3	0.6	15.5	0.4	0.3	0.3
20	20.9	0.4	0.5	0.4	20.0	0.3	0.2	0.2	20.7	0.4	0.3	0.3

	B 1				B 2				B 3			
Collector distance (m)	Drift distance (m)	Drift (%) Line A	Line B	Line C	Drift distance (m)	Drift (%) Line A	Line B	Line C	Drift distance (m)	Drift (%) Line A	Line B	Line C
0.5	0.6	1.7	13.8	2.3	0.5	9.6	23.2	2.0	0.5	10.1	8.5	4.1
1	1.1	0.8	3.6	2.5	1.0	3.6	21.1	0.7	1.0	3.1	6.6	2.3
2	2.3	0.4	0.6	2.7	2.0	3.1	5.7	0.6	2.0	0.8	2.7	3.2
3	3.4	0.3	0.6	1.7	3.1	0.8	0.3	0.5	3.0	0.7	0.7	0.8
5	5.6	0.2	0.4	0.9	5.1	0.5	2.3	0.4	5.0	0.4	0.5	0.6
10	11.3	0.2	0.1	0.2	10.2	0.4	0.4	0.2	10.1	0.2	0.4	0.4
15	16.9	0.2	0.1	0.2	15.3	0.2	0.3	0.1	15.1	0.2	0.2	0.2
20	22.5	0.3	0.1	0.1	20.4	0.2	0.2	0.1	20.1	0.1	0.2	0.1

	C 1				C 2				C 3			
Collector distance (m)	Drift distance (m)	Drift (%) Line A	Line B	Line C	Drift distance (m)	Drift (%) Line A	Line B	Line C	Drift distance (m)	Drift (%) Line A	Line B	Line C
0.5	0.5	0.6	2.7	0.3	0.5	0.8	1.3	1.5	0.5	0.9	0.2	0.9
1	1.0	0.5	0.7	0.2	1.0	0.4	1.7	0.6	1.1	0.7	0.6	0.8
2	2.1	0.4	0.6	0.1	2.0	0.2	0.4	0.5	2.1	0.4	0.4	0.7
3	3.1	0.3	0.4	0.1	3.0	0.2	0.3	0.4	3.2	0.4	0.4	0.4
5	5.2	0.2	0.3	0.1	5.0	0.2	0.2	0.3	5.3	0.2	0.2	0.3
10	10.4	0.1	0.1	0.1	10.1	0.1	0.2	0.2	10.6	0.1	0.1	0.2
15	15.6	0.1	0.1	0.1	15.1	0.1	0.1	0.1	15.8	0.1	0.1	0.1
20	20.8	0.1	0.1	0.1	20.2	0.1	0.1	0.1	21.1	0.1	0.1	0.1

	D 1				D2				D3			
Collector distance (m)	Drift distance (m)	Drift (%) Line A	Line B	Line C	Drift distance (m)	Drift (%) Line A	Line B	Line C	Drift distance (m)	Drift (%) Line A	Line B	Line C
0.5	0.5	2.8	2.3	4.2	0.5	16.5	10.0	3.1	0.5	22.5	4.2	4.9
1	1.0	4.1	3.4	3.0	1.0	7.0	10.5	2.2	1.1	3.3	1.7	1.8
2	2.1	0.5	0.5	0.6	2.0	0.8	1.9	0.4	2.1	1.7	0.7	1.0
3	3.1	0.3	0.3	0.4	3.0	2.5	0.8	0.5	3.2	1.5	0.6	0.8
5	5.2	0.3	0.3	0.3	5.0	0.7	0.6	0.3	5.3	0.9	0.5	0.7
10	10.3	0.2	0.2	0.2	10.0	0.4	0.3	0.3	10.7	0.5	0.4	0.5
15	15.5	0.1	0.2	0.1	15.0	0.2	0.2	0.1	16.0	0.4	0.4	0.4
20	20.7	0.1	0.1	0.1	20.1	0.2	0.1	0.1	21.4	0.4	0.4	0.4

	E 1				E 2				E 3			
Collector distance (m)	Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)		
		Line A	Line B	Line C		Line A	Line B	Line C		Line A	Line B	Line C
0.5	0.5	2.0	0.1	0.0	0.6	1.1	2.7	1.1	0.5	0.4	0.1	0.3
1	1.0	0.7	2.7	0.1	1.2	0.2	0.8	0.2	1.1	0.1	0.1	0.3
2	2.0	0.3	0.7	0.0	2.4	0.2	0.4	0.2	2.1	0.1	0.1	0.2
3	3.0	0.2	0.3	0.0	3.6	0.1	0.1	0.1	3.2	0.1	0.1	0.2
5	5.0	0.1	0.2	0.1	5.9	0.2	0.1	0.2	5.3	0.1	0.1	0.1
10	10.0	0.1	0.1	0.1	11.9	0.1	0.1	0.1	10.7	0.1	0.1	0.1
15	15.0	0.1	0.1	0.1	17.8	0.1	0.1	0.1	16.0	0.1	0.1	0.1
20	20.0	0.1	0.1	0.1	23.7	0.1	0.1	0.1	21.3	0.1	0.1	0.1

	F 2				F 3				F 4			
Collector distance (m)	Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)		
		Line A	Line B	Line C		Line A	Line B	Line C		Line A	Line B	Line C
0.5	0.6	6.2	21.2	2.3	0.6	3.5	9.0	13.5	0.5	8.6	15.2	14.6
1	1.2	2.2	8.7	2.4	1.2	2.1	2.6	5.3	1.0	5.3	9.4	6.4
2	2.4	0.5	0.8	1.1	2.4	1.2	0.7	0.5	2.0	2.0	6.3	4.6
3	3.5	0.5	0.6	0.7	3.6	1.4	0.7	0.5	3.0	1.3	4.6	4.1
5	5.9	0.5	0.5	0.4	6.1	0.7	0.5	0.4	5.0	0.7	1.7	1.8
10	11.8	0.4	0.4	0.4	12.1	0.3	0.4	0.3	10.0	0.3	0.6	0.5
15	17.7	/	0.4	0.4	18.2	0.3	0.3	0.3	15.0	0.3	0.3	0.4
20	23.6	/	0.4	0.4	24.2	0.3	0.3	0.3	20.0	0.3	0.3	0.3

	G 1				G 2				H 2			
Collector distance (m)	Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)		
		Line A	Line B	Line C		Line A	Line B	Line C		Line A	Line B	Line C
0.5	0.5	14.9	14.3	5.3	0.7	3.2	14.5	0.9	0.5	0.8	6.5	0.9
1	1.1	5.6	6.4	3.0	1.3	1.9	3.2	0.4	1.0	0.5	2.1	0.5
2	2.1	0.3	3.3	1.9	2.6	0.5	1.2	0.5	2.0	0.3	0.5	0.3
3	3.2	1.2	2.3	1.7	3.9	0.3	0.6	0.4	3.1	0.3	0.6	0.3
5	5.3	0.9	1.1	0.7	6.5	0.3	0.3	0.3	5.1	0.3	0.3	0.3
10	10.6	0.4	0.5	0.5	13.1	0.3	0.3	0.3	10.2	0.3	0.3	0.3
15	15.9	0.4	0.4	0.4	19.6	0.3	0.2	0.3	15.3	0.3	0.3	0.3
20	21.2	0.4	0.4	0.3	26.1	0.3	0.2	0.3	20.4	0.3	0.3	0.3

	H 3				H 4				I 1$			
Collector distance (m)	Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)		
		Line A	Line B	Line C		Line A	Line B	Line C		Line A	Line B	Line C
0.5	0.7	0.4	0.3	0.7	0.5	1.2	3.1	3.6	0.6	12.9	13.9	19.6
1	1.3	0.3	0.3	0.4	1.1	1.0	1.6	0.8	1.1	7.4	6.7	8.0
2	2.7	0.3	0.3	0.4	2.2	0.5	0.8	0.7	2.2	5.7	7.3	2.7
3	4.0	0.3	0.3	0.3	3.3	0.4	0.6	0.5	3.3	4.9	5.9	1.9
5	6.7	0.2	0.3	0.3	5.4	0.3	0.4	0.3	5.5	2.2	1.5	1.8
10	13.3	0.3	0.2	0.3	10.9	0.2	0.3	0.3	11.0	0.6	0.5	0.6
15	20.0	0.2	0.2	0.3	16.3	0.2	0.3	0.3	16.5	0.5	0.3	0.5
20	26.6	0.3	0.2	0.2	21.7	0.2	0.3	0.3	22.0	0.4	0.3	0.5

		I 2				I 3				J 1		
Collector distance (m)	Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)		
		Line A	Line B	Line C		Line A	Line B	Line C		Line A	Line B	Line C
0.5	0.5	4.9	8.7	/	0.6	2.5	9.1	9.6	0.6	1.6	6.7	2.6
1	1.1	4.1	4.4	/	1.2	1.1	3.2	2.6	1.1	0.9	2.2	1.1
2	2.1	1.4	1.1	/	2.4	0.4	0.8	1.1	2.2	1.2	0.8	1.0
3	3.2	0.9	0.8	/	3.7	0.3	1.1	0.8	3.3	1.1	1.3	0.3
5	5.3	0.5	0.4	/	6.1	0.3	0.4	0.3	5.5	0.3	0.4	0.4
10	10.7	0.6	0.4	/	12.2	0.2	0.2	0.2	11.1	0.4	0.2	0.2
15	16.0	0.5	0.3	/	18.4	0.2	0.2	0.2	16.6	0.3	0.2	0.1
20	21.4	0.3	0.2	/	24.5	0.2	0.2	0.2	22.1	0.4	0.2	0.1

		J 2				J 3				K 2		
Collector distance (m)	Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)		
		Line A	Line B	Line C		Line A	Line B	Line C		Line A	Line B	Line C
0.5	0.5	3.4	10.0	1.0	0.5	2.8	5.6	1.2	0.9	17.7	47.7	23.3
1	1.0	0.4	7.8	0.4	1.1	1.7	2.2	0.4	1.9	6.3	16.9	11.3
2	2.0	1.5	3.0	0.4	2.1	1.5	1.7	0.3	3.7	2.7	3.7	6.4
3	3.0	0.4	0.2	0.4	3.2	0.3	0.7	0.1	5.6	2.9	0.9	2.5
5	5.0	0.3	1.7	0.3	5.3	0.2	0.3	0.1	9.3	1.1	1.0	0.2
10	10.0	0.3	0.2	0.2	10.5	0.1	0.2	0.1	18.6	0.4	0.1	0.1
15	15.0	0.1	0.2	0.1	15.8	0.1	0.2	0.1	28.0	0.1	0.1	0.1
20	20.1	0.1	0.1	0.1	21.0	0.1	0.1	0.1	37.3	0.1	0.1	0.1

		K 3				K 4				K 5		
Collector distance (m)	Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)		
		Line A	Line B	Line C		Line A	Line B	Line C		Line A	Line B	Line C
0.5	1.2	3.9	2.9	30.7	0.5	8.7	17.7	11.3	0.6	4.2	13.0	2.4
1	2.3	3.1	2.2	20.5	1.0	5.2	11.2	4.9	1.3	3.8	4.8	1.2
2	4.6	3.1	1.9	5.9	2.1	3.9	6.6	3.3	2.5	3.2	3.0	1.0
3	6.9	1.2	0.7	4.6	3.1	2.4	4.4	2.4	3.8	2.0	3.0	0.9
5	11.5	0.3	0.6	0.5	5.2	1.7	3.0	2.1	6.3	1.5	1.2	0.8
10	23.0	0.2	0.3	0.5	10.3	1.3	1.1	1.0	12.6	0.5	0.5	0.5
15	34.5	0.3	0.3	0.3	15.5	1.3	0.9	0.8	18.9	0.4	0.5	0.7
20	46.0	0.1	0.3	0.3	20.7	0.9	0.8	0.7	25.2	0.3	0.4	0.5

		K 6				L 2				L 3		
Collector distance (m)	Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)		
		Line A	Line B	Line C		Line A	Line B	Line C		Line A	Line B	Line C
0.5	0.5	9.3	12.5	10.9	0.6	0.2	9.8	36.6	0.6	7.5	10.4	42.2
1	1.0	7.1	6.9	6.2	1.2	0.7	0.9	25.4	1.2	6.2	7.0	29.4
2	2.0	4.6	3.0	4.5	2.5	1.7	0.9	2.0	2.4	2.4	0.7	5.9
3	3.0	2.8	2.5	1.7	3.7	0.6	0.5	1.7	3.6	0.7	0.2	1.9
5	5.0	1.8	1.0	1.3	6.2	0.3	0.3	0.3	6.1	0.1	0.5	0.5
10	10.0	0.9	0.4	0.7	12.4	0.2	0.2	0.8	12.1	0.0	0.1	0.3
15	15.0	0.5	0.3	0.5	18.7	0.1	0.2	0.2	18.2	0.1	0.1	0.1
20	20.0	0.4	0.3	0.4	24.9	0.1	0.1	0.0	24.2	0.1	0.0	0.1

	L 5				L 6				M 3			
Collector distance (m)	Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)		
		Line A	Line B	Line C		Line A	Line B	Line C		Line A	Line B	Line C
0.5	0.6	0.4	2.4	0.4	0.5	10.4	4.3	15.6	0.6	1.0	1.5	18.2
1	1.2	0.4	0.7	0.2	1.0	5.8	1.4	5.2	1.3	1.1	1.4	7.2
2	2.3	0.4	0.4	0.3	2.0	2.9	0.8	2.3	2.5	0.3	0.9	0.3
3	3.5	0.4	0.2	0.5	3.0	1.8	0.7	1.2	3.8	0.2	0.2	0.2
5	5.8	0.2	0.2	0.6	5.0	0.6	0.5	0.7	6.3	0.1	0.1	0.2
10	11.6	0.2	0.2	0.2	10.0	0.2	0.4	0.4	12.5	0.1	0.1	0.1
15	17.4	0.2	0.2	0.2	15.1	0.2	0.3	0.3	18.8	0.1	0.1	0.1
20	23.2	0.2	0.2	0.2	20.1	0.2	0.2	0.3	25.0	0.0	0.1	0.1
	M 4				M 5				N 1			
Collector distance (m)	Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)		
		Line A	Line B	Line C		Line A	Line B	Line C		Line A	Line B	Line C
0.5	0.6	1.7	4.3	5.1	0.5	6.0	6.4	10.4	0.6	30.8	9.1	3.8
1	1.2	1.2	1.5	2.0	1.0	2.8	2.7	4.3	1.1	8.7	3.7	0.0
2	2.4	1.0	1.1	1.4	2.0	1.3	2.0	1.7	2.3	0.3	1.9	1.9
3	3.6	0.8	1.1	1.0	3.0	0.9	2.1	1.3	3.4	0.3	0.5	1.8
5	6.0	0.5	0.8	1.0	5.0	0.8	1.1	0.5	5.7	0.3	0.2	0.5
10	12.0	0.5	0.4	0.5	10.0	0.4	0.4	0.4	11.4	0.2	0.4	0.2
15	18.0	0.3	0.3	0.4	15.0	0.3	0.3	0.3	17.0	0.2	0.2	0.2
20	24.0	0.3	0.3	0.4	20.0	0.3	0.2	0.3	22.7	0.2	0.2	0.2
	N 2				N 4				O 1			
Collector distance (m)	Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)		
		Line A	Line B	Line C		Line A	Line B	Line C		Line A	Line B	Line C
0.5	0.6	1.3	5.5	0.8	0.5	15.4	16.3	25.5	0.5	5.4	5.0	5.1
1	1.1	0.3	2.3	0.9	1.0	10.1	11.9	9.4	1.0	3.1	0.8	1.3
2	2.2	0.6	0.3	0.2	2.0	4.3	7.9	6.7	2.0	2.7	2.1	1.8
3	3.3	0.8	1.3	0.2	3.0	2.4	3.3	4.4	3.1	0.8	0.9	0.9
5	5.5	0.1	0.2	0.1	5.1	2.9	2.4	2.3	5.1	0.9	0.3	0.3
10	11.0	0.1	0.2	0.1	10.1	0.9	0.9	1.1	10.2	0.2	0.2	0.2
15	16.5	0.1	0.1	0.1	15.2	0.9	0.8	0.9	15.3	0.1	0.2	0.2
20	22.0	0.1	0.1	0.1	20.2	0.9	0.8	0.9	20.4	0.1	0.1	0.1
	O 2				O 3				P 1			
Collector distance (m)	Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)		
		Line A	Line B	Line C		Line A	Line B	Line C		Line A	Line B	Line C
0.5	0.6	0.9	1.1	0.3	0.5	8.7	20.0	20.1	0.6	12.1	8.2	19.5
1	1.1	0.7	0.9	1.1	1.0	4.5	10.9	10.7	1.2	3.3	3.2	8.5
2	2.3	0.2	0.8	0.5	2.1	3.2	5.9	5.0	2.3	1.2	1.3	1.8
3	3.4	0.2	0.7	0.3	3.1	1.5	2.8	2.6	3.5	0.9	0.6	0.9
5	5.7	0.2	0.2	0.5	5.2	1.1	1.7	1.0	5.9	0.6	0.4	0.2
10	11.4	0.1	0.2	0.2	10.4	0.6	0.8	0.6	11.7	0.1	0.1	0.5
15	17.1	0.1	0.1	0.1	15.5	0.4	0.5	0.4	17.6	0.0	0.1	0.1
20	22.8	0.1	0.1	0.1	20.7	0.3	0.4	0.4	23.5	0.0	0.0	0.1

		P 3			P 4				Q 1			
Collector distance (m)	Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)		
		Line A	Line B	Line C		Line A	Line B	Line C		Line A	Line B	Line C
0.5	0.5	13.7	40.0	17.3	0.5	19.0	20.3	9.3	0.6	1.7	2.9	9.9
1	1.0	8.3	25.5	10.1	1.0	6.2	15.4	8.1	1.1	1.2	2.3	3.1
2	2.0	5.6	9.9	5.6	2.0	3.2	6.3	4.6	2.2	0.9	1.0	1.8
3	3.1	3.5	5.5	2.7	3.1	2.3	6.0	2.5	3.3	0.7	0.9	1.3
5	5.1	3.8	1.2	1.5	5.1	1.7	3.9	1.6	5.6	0.7	0.6	0.7
10	10.2	1.0	0.6	0.8	10.2	0.9	1.1	1.4	11.1	0.5	0.6	0.7
15	15.3	0.8	0.5	0.6	15.3	0.7	0.6	1.0	16.7	0.5	0.6	0.6
20	20.4	0.5	0.5	0.5	20.3	0.5	0.6	0.7	22.2	0.5	0.6	0.5

		Q 2			Q 3				Q 4			
Collector distance (m)	Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)		
		Line A	Line B	Line C		Line A	Line B	Line C		Line A	Line B	Line C
0.5	0.5	1.6	2.8	4.8	0.5	2.6	7.4	2.5	0.5	2.6	3.2	22.2
1	1.1	1.0	2.2	1.6	1.0	1.4	3.0	1.8	1.1	1.1	1.0	9.9
2	2.2	0.9	1.2	1.0	2.0	0.9	2.1	1.2	2.1	0.8	0.9	1.3
3	3.2	0.8	0.7	0.9	3.1	0.7	1.6	0.8	3.2	0.7	0.6	1.2
5	5.4	0.7	0.8	0.8	5.1	0.6	1.2	0.7	5.3	0.6	0.7	0.7
10	10.8	0.6	0.8	0.6	10.2	0.5	0.7	0.7	10.6	0.5	0.5	0.6
15	16.2	0.6	0.6	0.5	15.3	0.5	0.5	0.5	15.9	0.5	0.5	0.6
20	21.6	0.5	0.6	0.6	20.5	0.5	0.5	0.5	21.2	0.5	0.5	0.6

		Q 5			R 1				R 2			
Collector distance (m)	Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)		
		Line A	Line B	Line C		Line A	Line B	Line C		Line A	Line B	Line C
0.5	0.6	2.8	1.4	15.3	0.5	13.2	3.0	23.7	0.5	12.4	4.0	41.9
1	1.2	1.0	1.2	10.6	1.0	4.3	2.1	7.5	1.1	7.7	2.9	14.6
2	2.4	0.7	1.2	1.7	2.0	1.5	1.3	2.7	2.2	1.6	1.6	4.0
3	3.7	0.7	0.9	0.8	3.0	1.3	1.0	0.9	3.2	1.2	1.0	1.5
5	6.1	0.6	0.6	0.6	5.1	0.9	0.7	0.6	5.4	0.8	0.8	0.9
10	12.2	0.5	0.5	0.5	10.1	0.5	0.6	0.6	10.8	0.5	0.6	0.6
15	18.3	0.5	0.5	0.5	15.2	0.5	0.5	0.5	16.1	0.5	0.5	0.5
20	24.4	0.5	0.5	0.5	20.3	0.4	0.5	0.4	21.5	0.4	0.4	0.4

		R 3			S 2				S 3			
Collector distance (m)	Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)		
		Line A	Line B	Line C		Line A	Line B	Line C		Line A	Line B	Line C
0.5	0.5	13.2	9.7	32.8	0.6	1.5	1.3	0.9	0.6	3.3	1.3	5.0
1	1.1	6.2	1.7	15.6	1.2	1.0	0.9	0.8	1.1	2.4	1.4	1.6
2	2.1	3.7	1.3	4.0	2.5	0.9	1.0	0.7	2.2	1.2	1.1	1.3
3	3.2	0.6	1.1	3.3	3.7	0.8	1.1	0.7	3.3	1.2	1.3	1.4
5	5.3	0.5	1.0	1.6	6.2	0.6	1.0	0.8	5.5	0.9	1.5	1.2
10	10.5	0.4	0.5	0.5	12.4	0.7	0.6	0.6	11.1	0.9	1.0	1.8
15	15.8	0.4	0.4	0.4	18.5	0.6	0.6	0.8	16.6	0.8	1.0	1.0
20	21.0	0.3	0.4	0.4	24.7	0.6	0.6	0.6	22.2	1.2	1.0	1.2

	S 4				S 5				T 1			
Collector distance (m)	Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)		
		Line A	Line B	Line C		Line A	Line B	Line C		Line A	Line B	Line C
0.5	0.6	1.1	1.1	1.4	0.5	2.7	8.2	8.2	0.6	12.7	5.5	2.9
1	1.2	0.8	0.8	0.9	1.0	1.5	7.8	3.6	1.1	5.3	3.0	0.8
2	2.5	0.8	0.6	0.9	2.1	0.7	1.5	1.1	2.2	1.0	0.7	0.4
3	3.7	0.6	0.6	0.6	3.1	0.6	0.7	1.0	3.3	0.5	0.4	0.4
5	6.2	0.5	0.5	1.0	5.2	0.6	0.6	0.8	5.5	0.4	0.4	0.4
10	12.4	0.5	0.6	0.8	10.4	0.6	0.6	0.6	11.1	0.3	0.3	0.3
15	18.7	0.5	0.5	0.5	15.6	0.6	0.6	0.6	16.6	0.3	0.3	0.3
20	24.9	0.5	0.5	0.6	20.8	0.6	0.6	0.6	22.1	0.3	0.3	0.3

	T 2				T 3			
Collector distance (m)	Drift distance (m)	Drift (%)			Drift distance (m)	Drift (%)		
		Line A	Line B	Line C		Line A	Line B	Line C
0.5	0.5	25.5	17.5	33.8	0.6	16.6	8.5	47.3
1	1.1	/	2.3	13.9	1.1	3.4	1.2	12.3
2	2.2	/	0.9	5.4	2.2	1.6	0.8	1.7
3	3.3	/	0.9	1.5	3.3	0.9	0.8	0.9
5	5.4	/	0.5	0.7	5.5	0.5	0.7	0.6
10	10.8	/	0.4	0.4	11.1	0.5	0.5	0.5
15	16.3	/	0.4	0.4	16.6	0.4	0.4	0.5
20	21.7	/	0.4	0.3	22.2	0.4	0.4	0.5

$^{\$}$ Spray boom too high during measurement

Annex 16: *DRP* values at different distances (+ sd) and DRP_t values (+sd) for the different other sprayings (A-T)

Experiments	A		B		C		D	
Nozzle type	F		LD		Injet		LD	
ISO nozzle size	02		02		02		03	
Pressure (bar)	3.0		3.0		3.0		3.0	
Speed (km.h^{-1})	8		8		8		8	
Boom height (m)	0.50		0.50		0.50		0.50	
Air assistance	no		no		no		no	
Distance (m)	*DRP* (%)	sd	*DRP* (%)	sd	*DRP* (%)	sd	*DRP* (%)	sd
0.5	-135.7	90.0	-9.7	57.1	81.6	10.6	32.9	26.0
1	-213.8	133.8	-36.9	111.8	77.3	6.5	21.7	38.0
2	-101.0	109.2	-22.3	71.8	70.9	7.5	65.4	5.6
3	-110.4	94.2	42.5	8.9	64.1	8.6	52.0	20.0
5	-130.3	26.6	-2.9	67.0	60.4	13.3	49.7	11.0
10	-165.2	152.8	18.1	30.7	52.9	11.2	35.0	19.5
15	-46.0	29.2	20.0	20.9	39.8	17.6	23.9	33.2
20	-48.5	27.2	7.5	19.8	31.5	23.7	14.0	45.9
DRP_t (%)	**-136.5**	**83.3**	**-3.6**	**56.2**	**67.2**	**9.7**	**38.4**	**11.9**

Experiments	E		F		G		H	
Nozzle type	Injet		F		LD		Injet	
ISO nozzle size	03		04		04		04	
Pressure (bar)	3.0		3.0		3.0		3.0	
Speed (km.h^{-1})	8		8		8		8	
Boom height (m)	0.50		0.50		0.50		0.50	
Air assistance	no		no		no		no	
Distance (m)	*DRP* (%)	sd	*DRP* (%)	sd	*DRP* (%)	sd	*DRP* (%)	sd
0.5	93.0	6.7	30.5	13.4	48.7	11.8	88.6	6.4
1	91.8	6.2	34.2	17.1	60.1	18.9	89.7	4.0
2	92.8	2.7	47.6	47.3	68.7	13.1	87.9	4.7
3	93.3	1.3	33.5	54.1	60.9	28.3	83.3	3.9
5	89.8	2.6	41.3	29.9	63.2	20.5	77.0	6.4
10	84.2	3.6	36.3	11.1	50.8	8.9	58.0	14.8
15	78.4	5.6	17.6	22.8	35.0	4.0	38.0	20.5
20	72.0	10.0	-3.7	34.0	11.1	5.6	16.3	26.0
DRP_t (%)	**89.8**	**3.8**	**33.9**	**20.8**	**54.9**	**15.4**	**77.7**	**4.3**

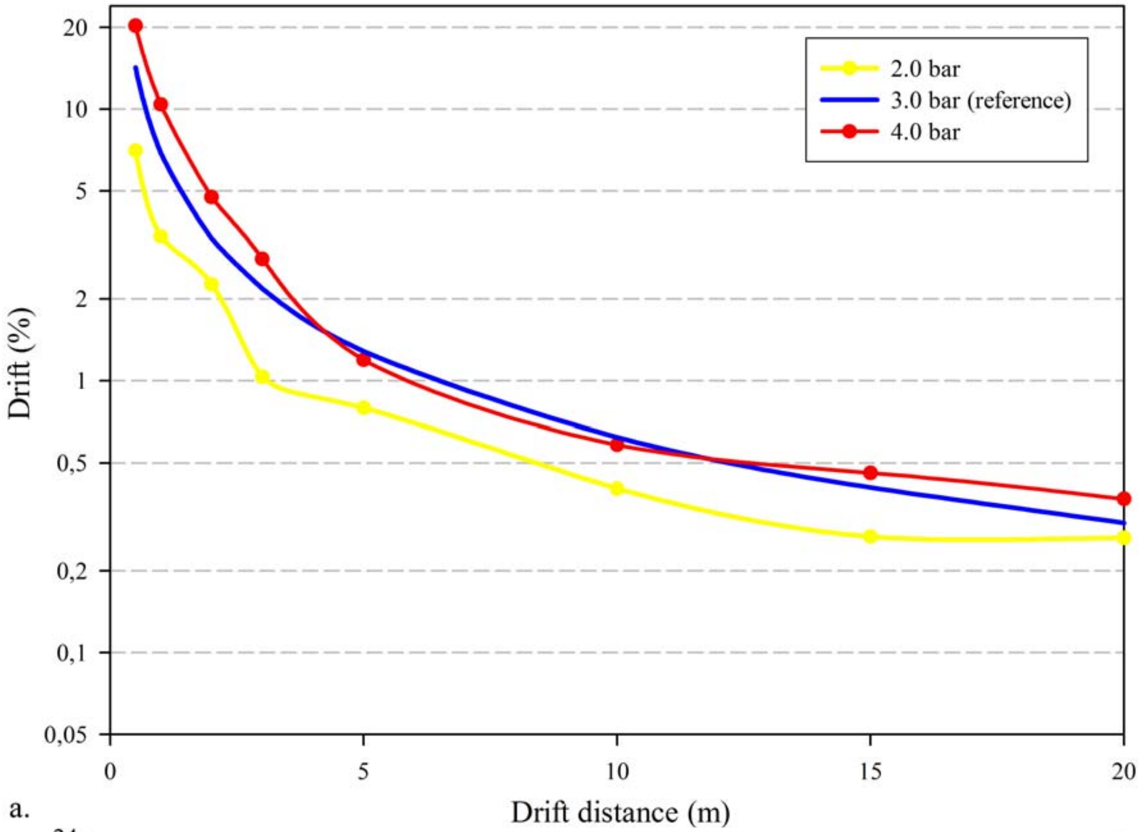
Experiments	I		J		K		L	
Nozzle type	F		F		F		F	
ISO nozzle size	06		03		03		03	
Pressure (bar)	3.0		2		4		3	
Speed (km.h^{-1})	8		8		8		4	
Boom height (m)	0.50		0.50		0.50		0.50	
Air assistance	no		no		no		no	
Distance (m)	*DRP* (%)	sd	*DRP* (%)	sd	*DRP* (%)	sd	*DRP* (%)	sd
0.5	20.6	17.0	50.6	8.8	-42.5	136.8	16.1	51.8
1	25.9	18.3	50.8	18.8	-50.9	125.2	-1.1	77.1
2	53.9	7.3	32.3	13.8	-42.1	85.6	46.2	26.7
3	43.6	5.5	52.8	32.0	-28.2	66.5	56.7	15.2
5	51.6	0.5	38.0	38.9	7.0	18.6	64.1	13.2
10	13.8	34.6	35.2	25.3	6.2	34.4	51.2	21.3
15	-3.3	37.5	34.1	31.3	-13.2	52.9	51.4	24.7
20	-9.0	13.3	11.9	65.1	-22.6	53.0	43.9	37.0
DRP_t (%)	**29.5**	**6.0**	**43.1**	**15.1**	**-27.1**	**70.1**	**35.3**	**24.8**

Experiments	M		N		O		P	
Nozzle type	F		F		F		F	
ISO nozzle size	03		03		03		03	
Pressure (bar)	3.0		3.0		3.0		3.0	
Speed (km.h^{-1})	6		10		8		8	
Boom height (m)	0.50		0.50		0.30		0.75	
Air assistance	no		no		no		no	
Distance (m)	*DRP* (%)	sd	*DRP* (%)	sd	*DRP* (%)	sd	*DRP* (%)	sd
0.5	55.6	14.0	9.8	66.9	48.4	44.4	-60.6	59.7
1	59.6	12.6	19.9	73.1	44.1	46.7	-67.2	31.8
2	63.3	21.7	15.4	99.6	23.3	45.4	-41.6	45.5
3	56.3	32.9	21.9	71.9	41.7	29.3	-40.2	73.4
5	50.0	36.5	18.5	108.4	38.1	21.0	-46.6	97.4
10	43.8	40.2	21.1	78.3	38.4	26.8	-33.6	92.9
15	37.7	42.0	3.3	112.6	37.8	25.1	-34.0	110.9
20	16.5	59.9	-30.1	151.7	27.5	31.1	-40.8	119.4
DRP_t (%)	**52.9**	**20.6**	**14.6**	**81.7**	**40.1**	**34.6**	**-49.9**	**52.3**

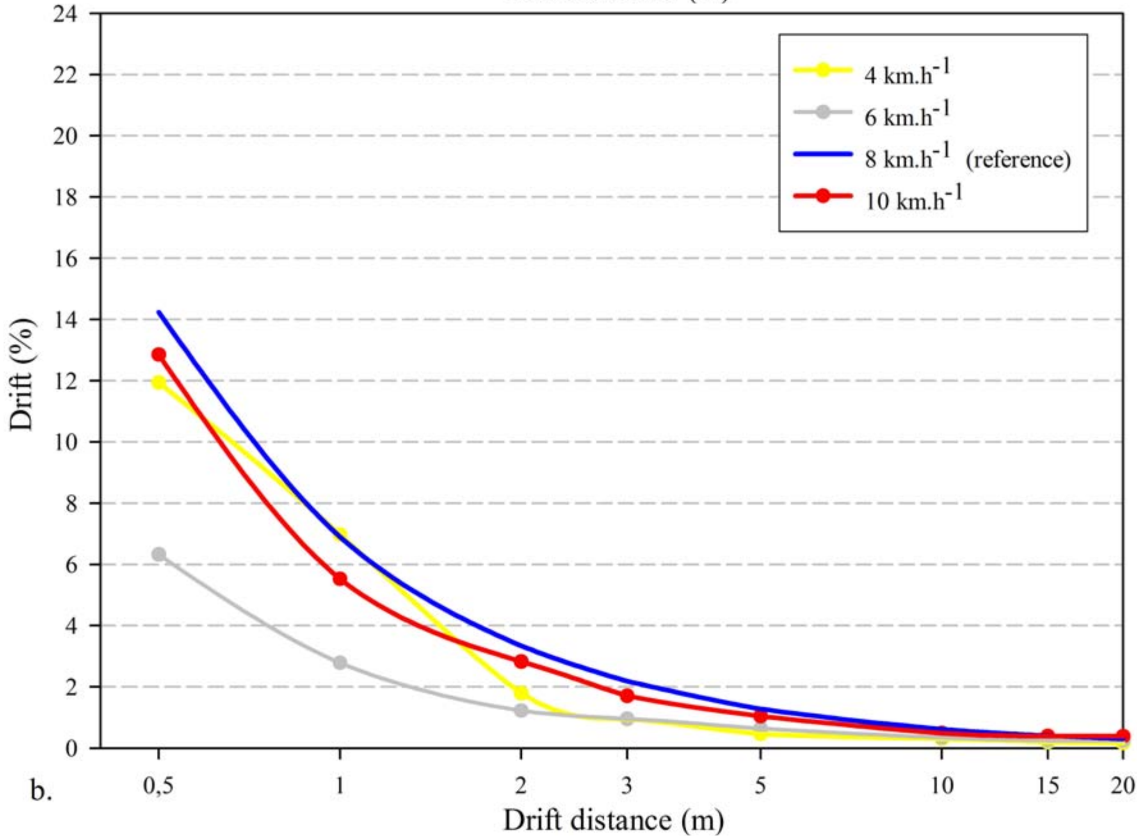
Experiments	Q		R		S		T	
Nozzle type	F		F		LD		LD	
ISO nozzle size	02		03		0		03	
Pressure (bar)	3.0		3.0		3.0		3.0	
Speed (km.h^{-1})	8		8		8		8	
Boom height (m)	0.50		0.50		0.50		0.50	
Air assistance	yes		yes		yes		yes	
Distance (m)	*DRP* (%)	sd	*DRP* (%)	sd	*DRP* (%)	sd	*DRP* (%)	sd
0.5	19.0	50.7	26.7	15.6	78.6	12.0	-11.0	48.8
1	13.0	62.2	38.5	18.9	71.0	16.0	31.0	22.6
2	31.5	20.7	56.4	7.8	65.7	4.9	56.7	28.0
3	21.4	16.6	63.2	5.1	52.7	15.2	66.9	9.7
5	-4.1	17.6	59.8	4.0	23.1	23.8	63.7	3.0
10	-82.1	36.3	47.1	11.7	-48.0	54.9	42.4	3.8
15	-159.3	67.2	30.2	17.0	-97.2	53.2	19.3	8.6
20	-238.2	92.1	18.1	14.5	-178.7	95.8	-6.2	11.4
DRP_t (%)	**-13.6**	**38.8**	**43.5**	**9.2**	**32.2**	**14.3**	**32.2**	**18.3**

DRP, drift reduction potential; DRP_t, total drift reduction potential; F, Hardi ISO 110 standard flat fan nozzles; LD, Hardi ISO 110 low-drift nozzles; Injet, Hardi ISO Injet air inclusion nozzles

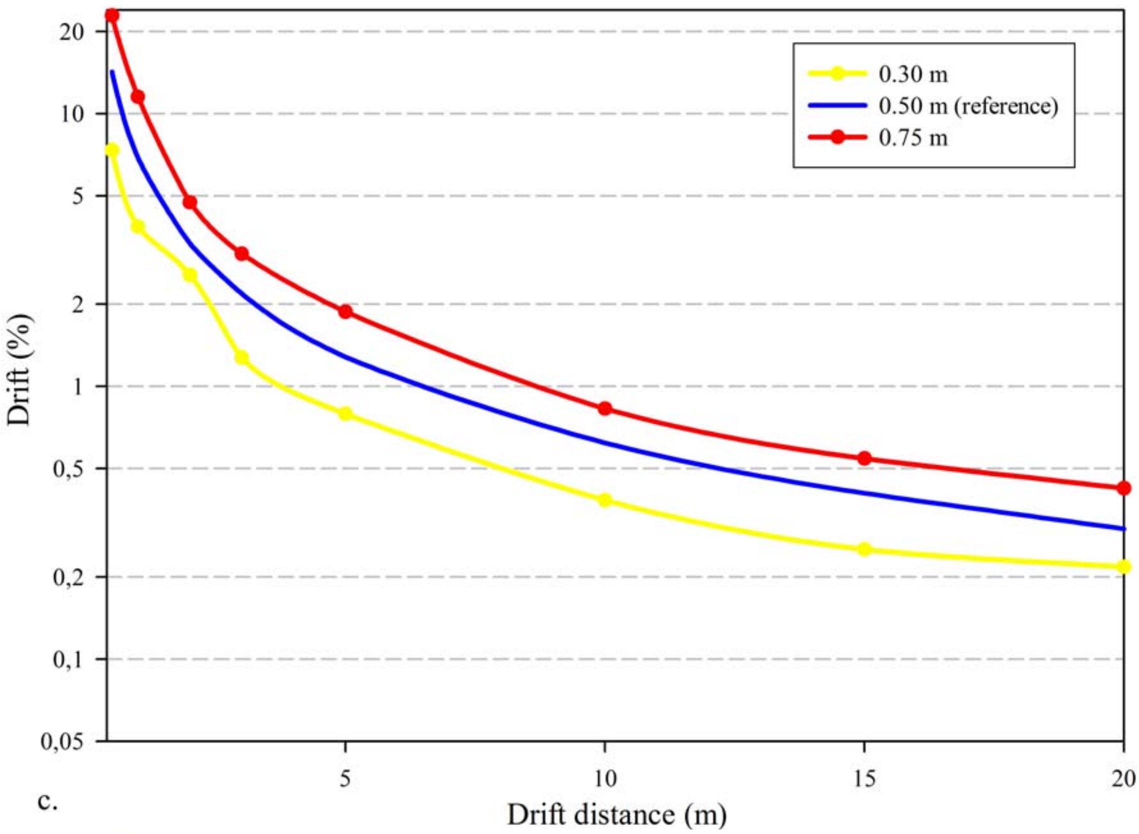
Annex 17: Predicted sedimenting drift curves for Hardi ISO F 110 03 standard flat fan nozzles at standard meteorological conditions (T = 16°C, $V_{3.25m}$= 3 m.s^{-1} and X_{H_2O}= 8 g.kg^{-1}) to illustrate the effect of a. spray pressure (2.0, 3.0 and 4.0 bar) b. driving speed (4, 6, 8 and 10 km.h^{-1}) c. spray boom height (0.30, 0.50 and 0.75 m) and d. air assistance for Hardi ISO F 110 02, F 110 03, LD 110 02, LD 110 03 nozzles at 3.0 bar, 8 km.h^{-1} and 0.50 m boom height



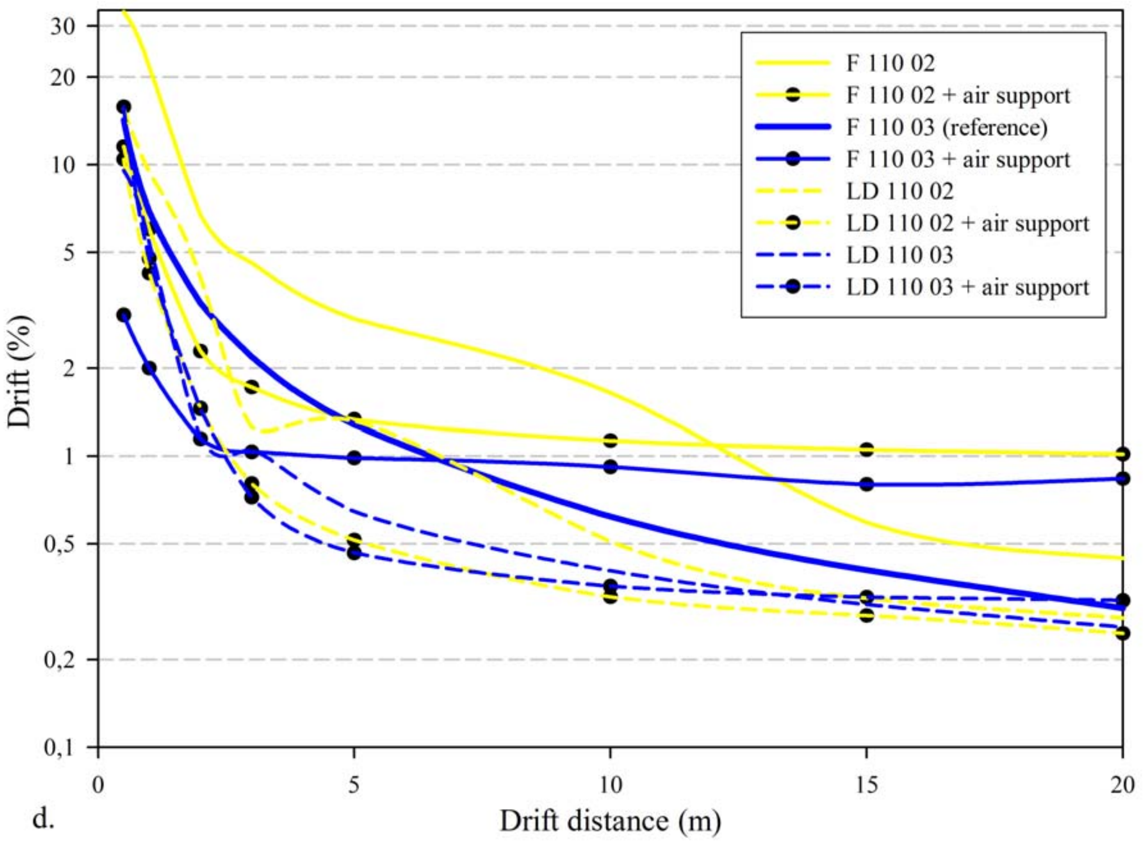
a.



b.

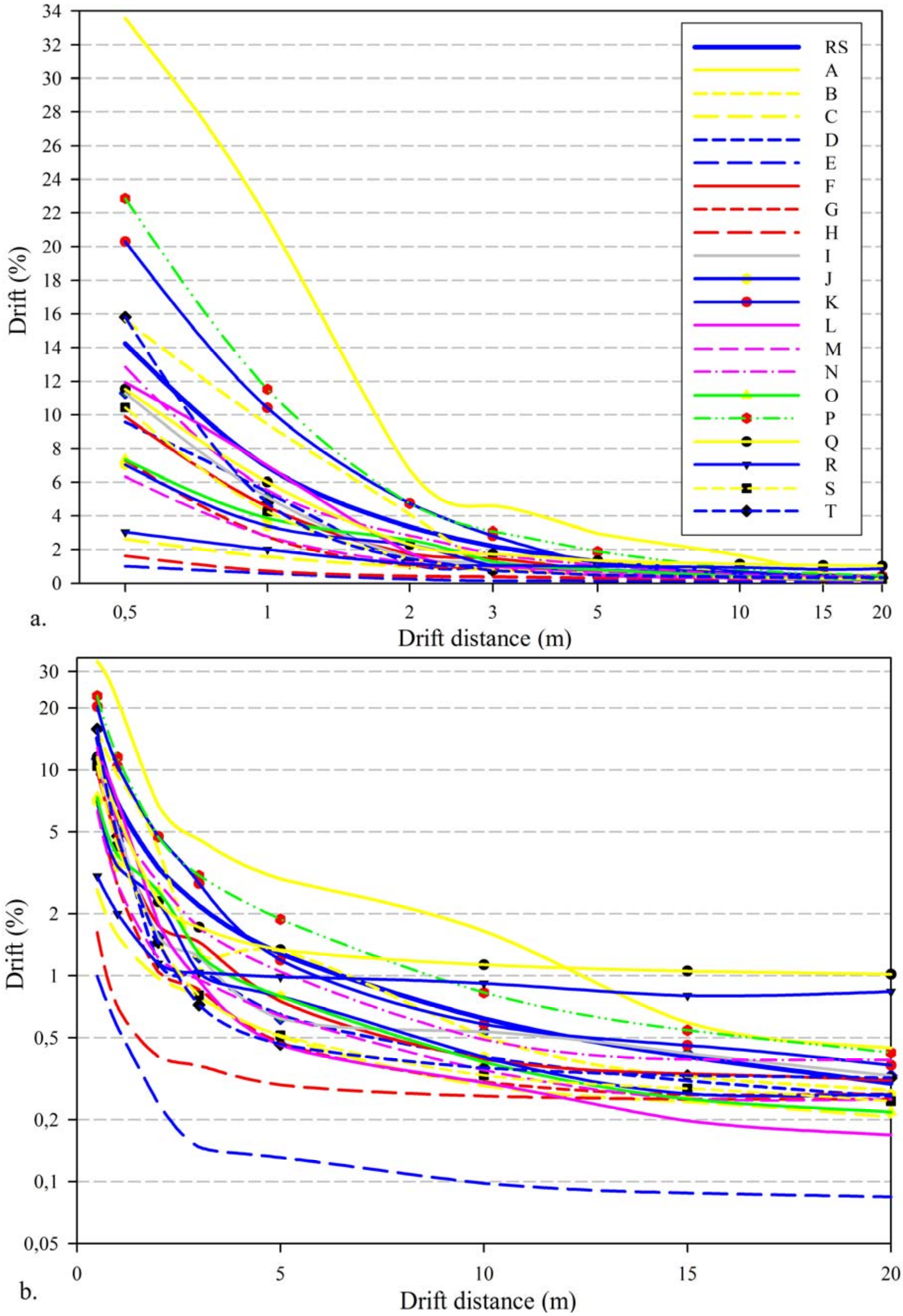

0.30 m
0.50 m (reference)
0.75 m
Drift (%)
20
10
5
2
1
0,5
0,2
0,1
0,05
5
10
15
20
Drift distance (m)

c.


F 110 02
F 110 02 + air support
F 110 03 (reference)
F 110 03 + air support
LD 110 02
LD 110 02 + air support
LD 110 03
LD 110 03 + air support
Drift (%)
30
20
10
5
2
1
0,5
0,2
0,1
0
5
10
15
20
Drift distance (m)

d.

Annex 18: Predicted sedimenting drift curves for the different spray application techniques investigated in this study (RS, A-T) described in Table 5.1 at standard meteorological conditions (T = 16°C, $V_{3.25m}$= 3 m.s^{-1} and X_{H_2O}= 8 g.kg^{-1}) with a. a logarithmic scale of the X-axis b. a logarithmic scale of the Y-axis



Annex 19: Pearson correlation matrix for the different droplet characteristics

	D_{10}	D_{20}	D_{30}	D_{32}	$D_{v0.1}$	$D_{v0.25}$	$D_{v0.5}$	$D_{v0.75}$	$D_{v0.9}$	RSF	$D_{v0.5}$/NMD	NMD	V_{50}	V_{75}	V_{100}	V_{150}	V_{200}	V_{250}	v_{vol10}	v_{vol25}	v_{vol50}	v_{vol75}	v_{vol90}	VSF	v_{avg}
D_{10}	1																								
D_{20}	1	1																							
D_{30}	1	1	1																						
D_{32}	0.98	0.99	1	1																					
$D_{v0.1}$	0.99	1.00	1	1	1																				
$D_{v0.25}$	0.98	0.99	1	1	1	1																			
$D_{v0.5}$	0.97	0.98	0.99	1	0.99	1	1																		
$D_{v0.75}$	0.96	0.97	0.98	0.99	0.98	0.99	1	1																	
$D_{v0.9}$	0.93	0.94	0.96	0.97	0.96	0.97	0.98	0.99	1																
RSF	-0.91	-0.91	-0.91	-0.90	-0.91	-0.90	-0.89	-0.86	-0.78	1															
$D_{v0.5}$/NMD	-0.40	-0.39	-0.37	-0.33	-0.38	-0.32	-0.27	-0.25	-0.23	0.39	1														
NMD	0.99	0.99	0.98	0.96	0.97	0.96	0.95	0.93	0.89	-0.90	-0.42	1													
V_{50}	-0.85	-0.86	-0.87	-0.89	-0.88	-0.89	-0.90	-0.91	-0.90	0.82	0.13	-0.80	1												
V_{75}	-0.82	-0.84	-0.85	-0.88	-0.86	-0.87	-0.88	-0.90	-0.90	0.79	-0.82	-0.76	0.98	1											
V_{100}	-0.81	-0.83	-0.84	-0.87	-0.86	-0.86	-0.87	-0.89	-0.89	0.78	0.22	-0.75	0.98	1	1										
V_{150}	-0.82	-0.84	-0.86	-0.88	-0.87	-0.88	-0.89	-0.91	-0.91	0.79	0.20	-0.77	0.98	1	1	1									
V_{200}	-0.85	-0.87	-0.88	-0.90	-0.89	-0.90	-0.91	-0.93	-0.93	0.79	0.15	-0.80	0.99	0.99	0.99	0.99	1								
V_{250}	-0.88	-0.90	-0.91	-0.93	-0.91	-0.92	-0.93	-0.95	-0.95	0.81	0.14	-0.84	0.99	0.98	0.97	0.98	1	1							
v_{vol10}	0.72	0.75	0.77	0.81	0.79	0.80	0.81	0.85	0.88	-0.56	-0.13	0.67	-0.72	-0.77	-0.77	-0.78	-0.80	-0.81	1						
v_{vol25}	0.68	0.71	0.73	0.77	0.75	0.76	0.78	0.82	0.85	-0.54	-0.10	0.62	-0.71	-0.76	-0.77	-0.78	-0.79	-0.80	0.99	1					
v_{vol50}	0.44	0.47	0.50	0.55	0.52	0.54	0.57	0.62	0.68	-0.29	0.11	0.37	-0.61	-0.66	-0.67	-0.68	-0.69	-0.68	0.89	0.92	1				
v_{vol75}	-0.06	-0.03	-0.01	0.04	0.01	0.03	0.06	0.13	0.22	0.23	0.34	-0.11	-0.20	-0.24	-0.25	-0.26	-0.27	-0.25	0.52	0.58	0.83	1			
v_{vol90}	-0.41	-0.39	-0.37	-0.32	-0.36	-0.34	-0.30	-0.24	-0.14	0.58	0.49	-0.45	0.17	0.14	0.13	0.13	0.12	0.14	0.20	0.26	0.56	-0.82	1		
VSF	-0.86	-0.88	-0.90	-0.92	-0.91	-0.92	-0.93	-0.94	-0.94	0.80	0.23	-0.81	0.91	0.94	0.93	0.94	0.95	0.95	-0.91	-0.87	-0.74	-0.27	0.12	1	
v_{avg}	0.15	0.17	0.19	0.22	0.19	0.21	0.23	0.28	0.36	0.09	0.18	0.13	-0.14	-0.18	-0.18	-0.20	-0.23	-0.25	0.67	0.70	0.80	0.83	0.75	-0.34	1