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Managing pesticide use in arable agriculture by improving nozzle selection based on product efficacy to give optimised use and improved spray drift control

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1. Abstract

This project aimed at developing an extended spray/nozzle classification scheme that could accommodate a wider range of nozzle designs than existing schemes and particularly including air-induction nozzles. The extended scheme would have components relating to possible product efficacy and the risk of spray drift as separate elements. The work was based on an initial hypothesis that had two components:

1) there is a negative correlation between product efficacy and deposit variability, so that data relating to deposit variability measured according to specific protocols could be used in an extended classification scheme; and
2) a spray drift risk parameter could be obtained from comparative spray drift measurements made to defined protocols in wind tunnel or field conditions.

Measurements of spray deposits on stainless steel rods in laboratory conditions showed that the highest levels of variability were associated with nozzles and application variables that gave good levels of efficacy when treating the main arable crops with boom sprayers, and therefore the first components of the initial hypothesis, were rejected. Further measurements with a wide range of nozzle designs gave deposit/droplet size relationships that indicated the potential for an efficacy classification based on deposit quantity, but the resolution and experimental repeatability were not sufficient to enable a revised classification approach to be defined at this stage. However, the work did deliver:

- results that supported the approach taken in the AHDB Cereals & Oilseeds Nozzle Guide including considering air-induction nozzles as either “small droplet” or “large droplet”;
- evidence that factors other than droplet size (particularly droplet velocity) are important in determining deposit on targets and could, therefore, be the basis for future work in developing classification systems;
- a specification for a revised test liquid for use in nozzle testing and spray application experiments that did not use a nonylphenol surfactant;
- data to show that application volumes of 75 to 100 L/ha gave deposits on small (<3.0 mm diameter) targets that were greater than at higher volumes;
- evidence that the deposition on small vertical targets was increased by more than a factor of two when the wind speed in the region between the nozzle and the target was increased within the range of acceptable conditions for field applications; and
- approaches that would enable a component of drift risk assessment to be included in an extended classification scheme.

2. Project summary

The current nozzle/spray classification schemes used in the UK (as the BCPC scheme), in the USA (as the ASABE standard) and elsewhere in the world are based on measurements of the droplet size distribution in sprays that are then compared with results from reference nozzles measured in the same way so as to define a spray quality for a given nozzle operating at a stated pressure. These classifications have been widely and successfully used on product labels, codes of practice and machinery operating manuals. However, they have not been well suited to classifying sprays with characteristics that are very different from those of the reference conventional nozzles or that have air-included droplets, such as those produced by air-induction nozzles. In particular, nozzle types producing large droplets that would be classified as coarse or very coarse with implications for low efficacy have been shown to give levels of efficacy that are higher than predicted from such classifications. This has important implications for nozzle selection when balancing efficacy with the need to control drift. This project aimed at developing an extended spray/nozzle classification scheme that could effectively accommodate a wider range of nozzle designs, particularly the air-induction nozzles. The extended scheme would have elements relating to possible product efficacy and the risk of spray drift as separate components. The work was based on an initial hypothesis that had two components, namely:

1) there is a negative correlation between product efficacy and deposit variability, so an extended nozzle/spray classification scheme could be derived from data relating to deposit variability when a defined target matrix was sprayed and sampled according to specific protocols: this was formulated based on the results from earlier project work that showed higher coefficients of variation of measured deposits on artificial targets; and
2) that a spray drift risk parameter could be obtained from comparative spray drift measurements made to defined protocols in wind tunnel or field conditions: as in (1) above, this was based on results from a previous study.

There was a need to establish a test liquid that could be used in nozzle testing and experiments to assess spray deposition performance since the reference liquid specified in the BCPC scheme used a nonylphenol surfactant and such materials are no longer available in Europe. Measurements of the droplet size distributions with a range of nozzle types and sizes spraying different commercially available surfactants showed that there was no existing surfactant that would directly mimic that used as a previous reference. Experiments with Tween surfactants that have applications wider than agricultural plant protection products identified Tween 20 and Tween 80 as potential components for a reference spray liquid. Further measurements of the droplet size distributions and the recoveries of tracer dye solutions containing these surfactants showed that both could be used in water as a reference spray liquid and Tween 20 was, therefore, selected because of it better handling characteristic.

The first component of the hypothesis was explored by treating a defined matrix of stainless steel rods of 1.0 and 2.0 mm diameter supported both vertically and horizontally with a three nozzle boom in the wind tunnel on the Silsoe site. A tracer dye solution was applied using a range of nozzle conditions and deposits on individual rods were quantified using spectrophotometric techniques. Initial experiments examined the distribution pattern across the sampled area to establish and confirm that any spatial variability in the target region would not obscure smaller scale effects at the target level that were likely to be relevant to nozzle/spray classification. The distribution of deposits on individual rods was then assessed when applications were made at a nominal 100 L/ha when directly comparing conventional and “large droplet” air-induction nozzles, at different application volumes from 75 to 225 L/ha without changing the droplet distribution by using a multiple boom arrangement and with a wider range of nozzle types. Results from these measurements showed:

a) the distribution of deposits across the small swath treated with different nozzle types was approximately uniform such that “patternation” distribution effects could be excluded from the analysis;
b) deposits on rods supported horizontally were consistently greater than deposits on the same sized rods supported vertically;
c) greater deposits were measured when applications were made in a low velocity air flow with conventional flat fan nozzles compared with those from large droplet air-induction nozzles: the largest differences were measured when treating the smallest target size (1.0 smm diameter rods) and with the rods mounted vertically when deposits from the two nozzle types differed by more than a factor of two;
d) measured deposits on small vertical targets treated with sprays from a range of nozzle designs showed consistent trends with deposits decreasing as mean droplet size increased;
e) spray deposits measured with treatments applied using conventional flat fan nozzles in a multiple boom arrangement such that droplet size was not a factor, showed that higher deposits were associated with lower application volumes particularly for vertical targets;
f) the effect of wind speed at the target level was to substantially increase deposits on vertical targets when treatments were applied with conventional flat fan nozzles operating over a range of application volumes: wind speed had a very much smaller effect on the deposits on vertical targets treated with sprays from the large droplet air-induction nozzle and on deposits on targets supported horizontally.

It was noted that the results from the initial series of experiments did not support the original hypothesis since the variables that tended to give the greatest variability in measured deposits were known to be associated with generally higher levels of product efficacy in field conditions (i.e.

the use of conventional flat fan nozzles to make applications at circa 100 L/ha). A second series of deposit measurements were made on 1.0 mm rod targets supported both vertically and horizontally to further explore the potential for using measured spray deposits as a component in a nozzle/spray classification scheme representing likely product efficacy. Spray deposits were correlated with measured droplet size distributions and linked to the existing classification scheme.

Deposits on vertical 1.0 mm targets decreased when treatments were applied with conventional flat fan nozzles of increasing size (higher flow rates at a given pressure). This was recognised from the first series of experiments as being due to both the effect of increasing application volume and a larger droplet size. Deposits from pre-orifice and air-induction nozzles were higher than would have been expected, based on an extrapolation of the results for the conventional flat fan nozzles. Similar forms of relationship between measured deposits and the mean droplet size in the spray were recorded for the horizontal targets.

Combining the results of all deposits measurements made in the wind tunnel on the Silsoe site showed a considerable variability in the results obtained of which only some could be explained by differences in the experimental protocols used. However, some consistent trends were observed, namely:

1) deposits on horizontal targets were consistently higher than on the same targets supported vertically and subject to the same treatments;
2) deposits from treatments using air-induction nozzles were substantially greater than would have been predicted based on the results for the effects of droplet size obtained with conventional flat fan nozzles;
3) the slope of the spray deposit with droplet size relationship was shallower for air-induction nozzles than for conventional nozzles: air-induction nozzles were selected to give a range of (relatively large) droplet sizes at a single nozzle size (flow rate) – comparisons with conventional nozzles are therefore compounded since increasing droplet size with such conventional nozzles is related to higher flow rates and therefore increased application volumes.

Results from equivalent experiments conducted in a modified spray chamber at IPARC gave results that followed the same trends as those observed in experiments conducted in the Silsoe facilities.

It was concluded that direct measurement of deposits were unlikely to be sufficiently robust to be part of a spray/nozzle classification scheme mainly due to lack of repeatability in such measurements. However, the project did deliver results that have important implications for improving spray applications using boom sprayers, namely by providing:

- data that supported the approach taken in the AHDB Cereals & Oilseeds Nozzle Guide including considering air-induction nozzles as either “small droplet” or “large droplet”;
- evidence that factors other than droplet size (particularly droplet velocity) are important in determining deposit on targets and could therefore be the basis for future work in developing classification systems;
- a specification for a revised test liquid for use in nozzle testing and spray application experiments that did not use a nonylphenol surfactant;
- results to show that application volumes of 75 to 100 L/ha gave deposits on small (<3.0 mm diameter) targets that were greater than at higher volumes;
- results to show that the deposition on small vertical targets was increased by more than a factor of two when the wind speed in the region between the nozzle and the target was increased within the range of acceptable conditions for field applications: these wind speed conditions at target level could be related to recommended wind speeds for making spray applications that are measured at boom height; and
- approaches that would enable a component of drift risk assessment to be included in an extended classification scheme.

Measurements of droplet size and velocity distributions were used to calculate a retention parameter and impact energies and the results compared with the measured deposits on vertical and horizontal targets. Results for the computed retention parameter showed that performance for the different nozzle types used could be discriminated but that the match with measured deposits ranked the air-induction and pre-orifice nozzles incorrectly. Results from this part of the project indicate that there is the potential to derive a ‘deposit parameter’ based on the measurement of the physical parameters of a spray (droplet size, velocity and spray volume distributions) but that further work is needed to examine the relationships with measured deposits, the reliability of such methods and the effect of changing nozzle design variables including spray angle.

Measurements of spray drift in both field and wind tunnel conditions with systems regarded as both as having a high and a low drift risk showed that a scale of drift risk could be defined based on direct measurements downwind of an application system operating in a wind tunnel and made to a defined protocol. Details of such a scale and the terminology associated with such a scale would be the subject of a wider debate but it has been proposed that this could be based on an extension of the star rating system used in the existing Local Environmental Risk Assessment for Pesticides (LERAP) scheme. It was noticeable that while the trends in low drift performance gave relatively good agreement between measurements made in field and wind tunnel conditions, in the field tests the high drift scenarios tended to be under-recorded in comparison with results from wind tunnel tests. This probably related to airborne spray from full-sized application equipment reaching heights above those of the sampling matrices even though measurement in field conditions were made relatively close to the edge of a treated swath (5.0 and 10.0 m downwind).

3. Introduction

This project aimed at extending the existing British Crop Protection Council (BCPC) nozzle/spray classification scheme to a wider range of nozzle types including air-induction, twin-fluid nozzles and spinning discs, so that a better practical selection of nozzles could be used to improve both timeliness and drift control when applying plant protection products using conventional boom sprayers.

The existing spray classification scheme enables relative descriptions of the droplet size distribution from defined nozzles designs operating at stated pressures to be used on product labels and to define nozzle/sprayer performance in instruction books, manufacturers' literature and in codes of practice by defining classes of spray quality. The approach assumes that that there are relationships between the droplet size distribution and both likely efficacy and drift risk for nozzles operating on boom sprayers with some products. The approach has proved to be very useful particularly for classifying the performance of conventional downwardly directed hydraulic pressure nozzles. However, the implied relationships are much less robust for a wider range of nozzle types. The current scheme has limitations when classifying nozzles with spray characteristics that are very different from those of the reference nozzles. These fall into three main classes:

- Systems that generate sprays with different droplet size distribution/volume characteristics when compared with conventional flat fan nozzles – e.g. some designs of spinning discs;
- Systems that give sprays with different droplet size/velocity profiles e.g. some designs of air shear nozzle and some spinning disc designs;
- Sprays with "air-included" droplets such as those from air-induction and twin-fluid nozzles and that behave differently from conventional droplets both in-flight and on contact with a surface.

Sprays with these characteristics cannot be meaningfully classified within the existing scheme. An important feature of some examples of the above systems is their ability to control drift in comparison with conventional hydraulic pressure nozzles. A classification scheme that is inclusive of a wider range of nozzles would facilitate nozzle selection that can optimise efficacy, minimise pesticide use and control the risk of drift. Extending the existing scheme to include all of the above classes would enable most known agricultural pesticide application systems to be classified.

A spray/nozzle classification scheme should provide relative information relevant to efficacy and drift risk components of performance for systems operating in typical UK conditions. Results from the 2004 survey conducted by the Central Science Laboratory show that for machines operating over arable crops, this typically involved a forward speed of 10 to 12 km/h applying around 150 L/ha. This is a change from the situation in the 1980s when the existing scheme was devised and typical conditions were 200 L/ha applied at 8.0 km/h from a 12 m wide boom. This change, which is continuing, needs to be recognised in the revised classification system. A classification system needs to provide a means of grouping application methods in a way that enables a first tier route to specifying the type of nozzle to be used in given situations. It is unlikely to provide all the information that is required when making application decisions and risk assessments and information from other sources will need to be used in most circumstances.

3.1. The background to the existing BCPC nozzle/spray classification scheme and its development

Results from a wide range of studies examining the application of pesticides to arable crops have shown a relationship between product efficacy and the droplet size distribution generated by conventional hydraulic pressure nozzles. Some products, particularly grass weed herbicides, had a performance that was sufficiently dependent on the droplet size distribution that pesticide manufacturers considered, specifying particular nozzles and operating pressures as part of the label recommendation. This was considered undesirable because of the lack of flexibility in such an approach. The BCPC nozzle/spray classification (Doble *et al*., 1985) was devised to provide a more flexible approach with direct relevance to product efficacy and some implied reference to spray drift control. The relationship between droplet size and product efficacy was subsequently confirmed in a detailed review study published by Knocke (1994). The BCPC spray/nozzle classification scheme has been very successful in providing a means of communicating spray characteristics in label statements, advisory documents such as Codes of Practice and in literature specifying nozzle performance. It has been adopted in a range of forms by many countries throughout the world and especially in the USA where the American Society for Agricultural and Biological Engineering have published standards for nozzle classification based on the same principles.

The increasing need to consider spray drift and the acceptance that drift can be influenced by factors such as velocity and spray structure as well as droplet size led to the concept that direct measures of relative drift risk should be included in the classification system. A collaborative research project funded by the Ministry of Agriculture, Fisheries and Food (MAFF) was undertaken to examine protocols for determining the drift risk from different nozzle systems and the results from this study led to recommendations relating to wind tunnel protocols for spray nozzle testing to determine a measure of drift risk (Miller *et al*., 1993). A paper presented at the BCPC Conference in 1997 (Southcombe *et al*., 1997) proposed a revamping of the classification scheme to improve the definition of the boundaries between spray quality classes but with no changes to the droplet size distributions associated with the classification classes in the original scheme. The recommendations made involved a re-definition of the reference nozzles and these were subsequently accepted and implemented. The same paper also proposed that the classification scheme should have a separate component relating to the risk of drift for nozzles determined in wind tunnel tests. It was proposed that this could be determined by measuring a vertical airborne profile at a given distance downwind from the nozzle (as in the German DIX approach – see Herbst and Ganzelmeier, (2000)) or based on protocols coming from the earlier MAFF-funded collaborative study. Detailed measurement protocols were not agreed following the publication of this paper and the concept of including a measure of drift risk in the classification scheme was not effectively implemented.

Limitations to the scheme have been recognised particularly in relation to the ability to classify systems such as the spinning disc, and devices generating sprays having air included droplets. An initial proposal by Miller *et al.*, (2002) relating to the classification of sprays with air-included droplets suggested that a threshold value be set for the amount of included air in droplets in such sprays. Nozzles potentially considered as generating air-included sprays with levels of included air above this threshold, would then be classified as medium spray quality. This was based on information that suggested that:

(i) air-included droplets were generally large but their lower release velocities, particularly from air induction nozzles, and the ability to absorb energy on impact with a target surface meant that their retention characteristics were better than the equivalent size of droplet produced by conventional agricultural pressure nozzles;

(ii) air-included sprays did not perform well in situations that traditionally required fine or fine/medium sprays such as the treatment of small grass weeds with herbicides, and the application of non-systemic fungicides and insecticides;

(iii) there was little evidence at that time of differences in efficacy with different designs of air-induction nozzle producing different spray physical characteristics.

A number of studies have examined the performance of air-included sprays and their characterisation. The quantity of air included in droplets of a given size is of particular importance and three main methods of determining this have been devised (Faggion *et al.,* 2006). These are:

a) measuring the velocities of defined sizes of droplets at two positions in a spray and using ballistic calculations to determine an effective density of the droplets (Miller *et al.,* 1991; Butler Ellis *et al.*, 2002): this method requires instrumentation able to determine droplet velocities and entrained air conditions within the spray that are also needed for the calculation;

b) a measurement of impact force generated by a given volume of spray liquid (Faggion *et al.*, 2006): while this method has been shown to be effective in determining whether a spray can be regarded as “air-included”, it was not sufficiently sensitive to discriminate between different designs of air-induction nozzle for which direct measurements of the droplet size distribution had shown substantial differences;

c) the direct measurement of included air in spray captured from a nozzle (Combellack and Miller, 2001): while this method is recognised as being relatively simple and crude, experience has shown that it is effective (Faggion *et al.*, 2006).

3.2. Planned approaches and objectives

The planned work in this project had two major components, namely:

a) to demonstrate that deposit variability could be used as an indicator of efficacy within a revised classification scheme and establish relationships between physical spray characteristics, deposit variability and hence likely efficacy;
b) to examine relationships between different drift risk parameters and define a parameter to be used in a revised classification scheme.

A review of the performance of air-induction nozzles, initiated as part of a project funded by The Chemical Regulation Directorate and continued as part of work on this project (Butler Ellis *et al.*, 2008), showed that "small droplet air-induction nozzles" gave levels of efficacy with many targets that were comparable with that of conventional nozzles. The main exception to this rule was the treatment of small targets such as grass weeds at smaller than the three true leaf stage, when the larger droplet size distribution from "small droplet air-induction nozzles" resulted in lower levels of efficacy than treatments applied with conventional flat fan nozzles applying a fine/medium quality spray (Powell *et al.*, 2002 and 2003). Results from previous project work reported by Butler Ellis *et al.* (2007) in which the deposits on both vertical and horizontal artificial targets sprayed with different application systems gave small difference in mean deposit levels with the different application systems but higher variability when applications were made with large droplet air-induction nozzles. It should be noted that these measurements were made using relatively large targets and with applications made in nominally still air conditions. Given these observations, it was hypothesised that the more variable deposit distribution that would result from treating small targets with a coarser spray (Clipsham, 1980) then resulted in the reduced level of efficacy, and therefore that the variability of deposit distribution could be used as an indicator of efficacy in a revised spray/nozzle classification system.

Results from wind tunnel measurements and computer modelling studies have shown that, for most nozzle types mounted on a conventional boom structure and directed downwards, the droplet size distribution of the airborne drifting spray is approximately constant at distances of greater than 5.0 m for wind speeds in the order of 2.0 $m.s^{-1}$ at boom height. It was again hypothesised that the measured airborne flux at a distance of 5.0 m downwind of a boom sprayer could be used as a single measure of drift risk in a revised classification scheme given standardised protocols for making such measurements in field or wind tunnel conditions.

To test these two hypotheses, the following experimental programme was agreed:

1) Studies to determine the specification for a test liquid that could be used in measurements to classify nozzle performance.
2) Measurements in wind tunnel conditions to assess the variability in deposit distribution when spraying small targets having well-defined geometry.
3) Measurements of the airborne spray profiles 5.0 m downwind of nozzle systems operating on conventional booms in both field and wind tunnel conditions.

The reference spray liquid chosen for spray application research and nozzle performance assessment in the UK has for many years been water plus 0.1% Agral (Syngenta Crop Protection Ltd), a nonylphenol ethoxylate non-ionic surfactant, marketed as an agricultural adjuvant. Work in other countries in Europe and across the world used similar surfactants marketed under different names. A surfactant is required in order to reduce the surface tension of the liquid and thereby create a spray liquid that will be more representative of typical tank mixes than water alone. This has an impact on the droplet size produced by spray nozzles and retention of spray droplets on plants and other targets. It is particularly important when investigating the performance of nozzles which create air inclusions in droplets, since the ‘foam stability’ of the surfactant solution is likely to be a crucial factor. However, the potential adverse environmental impact of the use of nonylphenol ethoxylate surfactants has now resulted in them being phased out as agricultural surfactants in the EU and therefore an alternative surfactant for research and nozzle evaluation purposes was required.

4. MATERIAL AND METHODS

4.1. Defining a test liquid for nozzle performance assessments

4.1.1. Criteria for a replacement surfactant for “Agral”

The criteria for such a replacement were not easy to define: Agral itself had no specific properties that made it an obvious choice. It was probably chosen originally because it was widely available, commonly used and relatively cheap. There was therefore a large quantity of data generated using Agral or an equivalent product that resulted in it becoming the “standard” for application research and nozzle performance assessments. To retain compatibility between future assessments and previously obtained data, it was advantageous to select a surfactant that has a similar effect on spray generation and, if possible, spray retention. There was, therefore, a specific requirement to ensure that the classification of existing nozzles would not be radically changed by the chosen surfactant. In addition, it was important to ensure that there is no adverse interaction between the surfactant and any tracer used in spray drift or retention experiments. The final crucial criterion is that it should have health and safety and environmental profiles that should make it safe and easy to work with and unlikely to be taken off the market for the foreseeable future.

4.1.2. Measurement of droplet size distributions

To compare droplet size distributions when operating with different spray liquids, measurements of the droplet size distributions produced by a range of nozzles were made using a Malvern Instruments Ltd “Spraytec” instrument in the specialised spray chamber on the Silsoe site (Tuck *et al*., 1997). The nozzle conditions used for the study are summarised in Table 1.

Table 1. Nozzle conditions used for comparing droplet size distributions with different test liquids

Nozzle	Measured	
	Pressure, bar	Flow rate, L/min
Flat fan (Hardi International)	5.0	0.359
Flat fan (Hardi International)	5.0	2.008
Flat fan (Hardi International)	3.0	2.360
	1.7	1.189
Flat fan (Hardi International)	2.5	3.532
	1.7	2.93
	1.0	2.279
BCPC/ASABE reference nozzle	1.0	2.211
Air-induction (“small droplet” -	5.0	1.019
Billericay Farm Services)	1.0	0.445
Air-induction (“medium droplet” -	5.0	2.015
Hardi International)		
Air-induction (“medium droplet” -	3.0	0.772
Lechler GMBh)	2.0	0.634
	1.5	0.553

All nozzles except the BCPC/ASABE reference nozzle were 110° fan angle, the BCPC/ASABE nozzle having a nominal 65° angle. Sprays were sampled 350 mm below the nozzle tip by mounting nozzles on a computer-controlled x-y transporter system that was programmed such that the long axis of the spray passed through the sampling beam at a speed of 20 $mm.s^{-1}$. The flow rate to the nozzle was monitored by mounting the pressurised canister used to supply the spray liquid on a weighing platform the output of which was monitored by a computer. Spraying pressure was monitored by a transducer immediately upstream of the nozzle and controlled manually by varying air pressure into the supply canister. Temperatures of the spray liquid and air surrounding the spray were monitored using platinum resistance thermometers mounted close to the spray nozzle and were adjusted to be within 3.0°C by controlling liquid temperature.

4.1.3. Recovery and stability with a tracer dye

The stability and potential interactions between potential alternative surfactants and a water soluble tracer dye ("Green S – Sensient Colours UK Ltd) in solutions of 0.1 to 0.5% of the dye and 0.1% of surfactant were examined when stored in dark and daylight conditions over a 21 day period. Samples from prepared solutions were taken at 5, 7, 11, 14 and 20 days after preparation and the concentrations of dye determined by standard colorimetric techniques. The recovery of dye from paper and plastic surfaces that were loaded with a measured volume of dye plus surfactant solution was also assessed. Sample surfaces were loaded with 10, 15, 20, 25 and 30 µl quantities that were then allowed to dry before being recovered into a known volume of de-ionised water and the recovered dye quantified again by colorimetry. Treated surfaces were also stored for 15 days in the dark at room temperature prior to repeating the recovery assessment. For paper surfaces, the effect of storing samples with a high dye/surfactant loading was assessed by treating chromatography paper samples with a spray applying 650 µl of solution that was then stored either wet or dry. Recoveries were then assessed after 1, 2, 3, 4, 5, 6, 7, 11 and 13 days after treatment.

4.2. The measurement of deposit distributions on simplified stainless steel rod targets

4.2.1. Initial measurements in the wind tunnel on the Silsoe site

Results from earlier work (Butler Ellis *et al*., 2008) had used relatively large artificial targets when compared with grass weeds at early stages of growth. In defining the protocols to be used in this work, it was recognised that smaller targets needed to be used such that the effect of deposit variability could be studied (Clipsam, 1980). Previous work had shown that the use of stainless steel rods as a target matrix was a useful approach in the development of nozzle systems (T. Robinson, pers. comm.). An initial series of experiments was therefore conducted using an array of 13 equally spaced stainless steel rods of 1.0 and 2.0 mm diameter and 100 mm long supported in three rows both vertically and horizontally in the central 0.5 m wide strip below a three nozzle boom. The boom was mounted on a transporter in the wind tunnel on the Silsoe site (Figure 1).

Applications were made with the boom travelling at a speed of 10.0 km h^{-1} into a uniform wind speed of approximately 1.0 $m.s^{-1}$ measured at the height of the target array. Nozzles were supported at a height of 0.5 m above the centre of the target array and deposits on individual target rods were determined by spectrophotometry based on samples of the original spray liquid containing a tracer dye (0.2 % "Green S" – Sensient Colours UK Ltd) and a surfactant (0.1% Tween 20 – Croda Chemicals) taken from the spray nozzles. The transverse and longitudinal distribution patterns were examined in six replicated measurements to determine the extent of any patternation effects on the variability of deposits from two different nozzle types, a conventional flat fan and an air-induction design selected to give a large droplet size. The nozzles were operated at a pressure of 3.0 bar to give a nominal flow rate of 1.2 L min^{-1}.

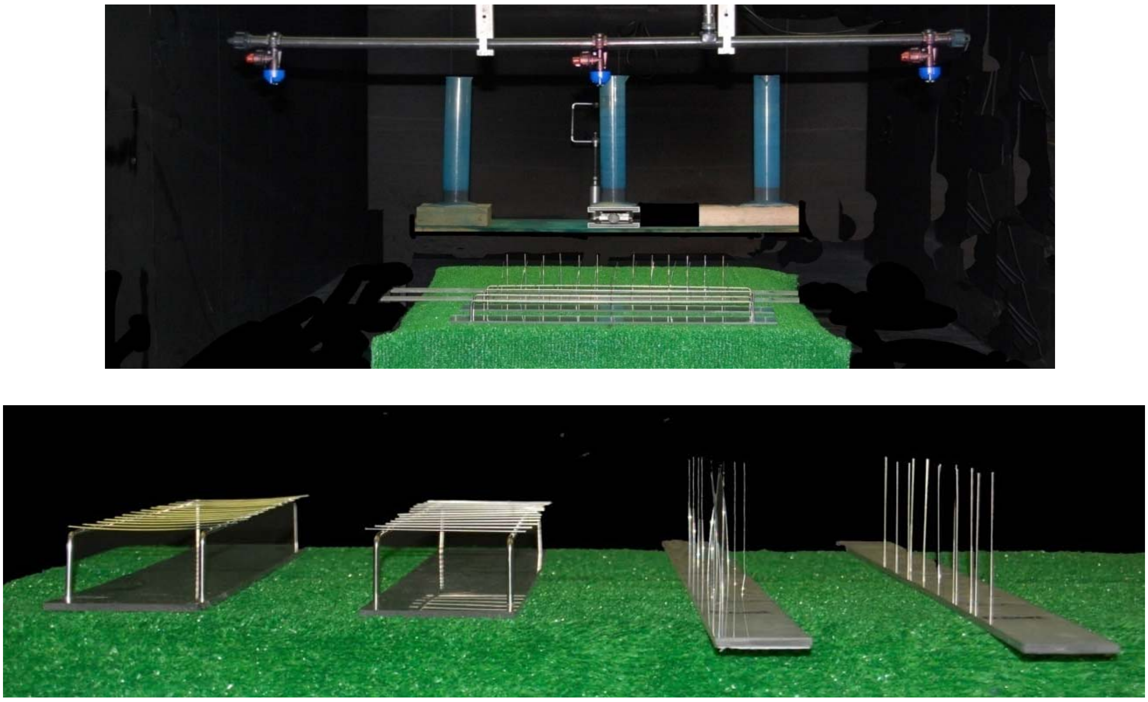


Figure 1. Boom arrangement and target systems used in wind tunnel studies at Silsoe

4.2.2. The effect of application volume and wind speed on deposits on stainless steel rods – wind tunnel measurements at Silsoe

A set of experiments examined the effects of application volume and wind speed on the magnitude and distribution of deposits on the 1.0 mm diameter rods. Application rate was varied without changing the droplet size distributions by using one, two or three booms operating simultaneously to apply nominally 75, 150 and 225 L ha^{-1}, using nozzles operating at 3.0 bar pressure to deliver 0.6 L min^{-1}. Measurements were made in nominally still air and with a head wind of approximately 1.0 m s^{-1} at the target level, and measurements were made with the boom travelling at 8.0 km h^{-1}. It was recognised that application volume could also be varied by varying forward speed and therefore a comparative treatment was included based on the single nozzle boom travelling at 4.0 km h^{-1} to apply 150 L $ha^{=1}$.

4.2.3. Measurements of deposit on stainless steel rods with different nozzle designs – measurements at Silsoe

The established protocols were used to examine the deposition patterns with different nozzle designs. Details of the nozzles used for this part of the study are summarised in Table 2. All nozzles were operated at a pressure of 3.0 bar. Measurements of droplet size and velocity distributions were made using an Oxford Lasers Ltd “Visisizer” instrument sampling the spray

0.35 m below the nozzle orifice with the nozzles spraying water only. The whole of the spray was sampled by mounting nozzles on an x-y transporter system that was programmed to move the nozzle such that the results obtained were relevant to the complete spray (Tuck *et al*., 1997). Volume median diameters shown in Table 2 are based on a temporal analysis and therefore the values are higher than for equivalent results from a spatial analysis. Droplet velocities are given for two mid-range droplet sizes nominally either side of the volume median diameter figure. The values obtained are consistent with expectations and show the extent of droplet size variation possible with different designs of air-induction nozzle delivering the same nominal flow rate.

Table 2. Nozzles used in the spray deposit study

Nozzle description	Flow rate, L/min	VMD, µm	% of spray volume <100 µm diameter	Mean droplet velocities, m/s	
				Mid-range 1, (µm)	Mid-range 2, (µm)
Conventional flat fan FF/110/0.8/3.0 (Hypro EU)	0.80	216.3	8.64	2.96 (170 – 190)	4.47 200 – 230)
Conventional flat fan FF/110/1.6/3.0 (Hypro EU)	1.60	292.4	4.45	5.83 210 – 230)	9.19 (280 – 300)
Conventional flat fan FF/110/2.4/3.0 (Hypro EU)	2.37	329.1	3.88	6.77 (230 – 240)	10.33 (310 – 340)
Pre-orifice flat fan LD/110/0.8/3.0 (TeeJet)	0.79	283.5	4.55	6.32 (210 – 230)	3.53 (270 – 300)
Pre-orifice flat fan LD/110/1.6/3.0 (TeeJet)	1.59	363.2	2.40	5.54 (250 – 270)	8.52 (350 – 380)
Pre-orifice flat fan LD/110/2.4/3.0 (TeeJet)	2.42	432.1	1.61	6.50 (280 – 300)	9.77 (410 – 440)
Air-induction “small droplet” AI/110/0.8/3.0 (TeeJet*)	0.77	417.1	1.51	4.57 (270 – 290)	6.57 (410 – 430)
Air-induction “medium droplet” AI/110/0.8/3.0 (TeeJet)	0.78	615.7	0.54	4.80 (370 – 390)	5.52 (600 – 630)
Air-induction “large droplet” AI/110/0.8/3.0 (TeeJet)	0.79	814.2	0.19	3.60 (470 – 490)	5.11 (800-820)

* - Note that a Lechler IDK nozzle (AI/120/0.8/3.0) was used in the initial experiment.

4.2.4. Measurements in a spray chamber at IPARC – establishing techniques

In developing techniques for classifying spray nozzle performance it was important to ensure that any measurements could be made in a range of environments and not just those relating to the wind tunnel on the Silsoe site. Initial experiments were therefore carried out with modifications to the IPARC ‘Mardrive’ at Silwood Park, as shown in Figure 2, with a double nozzle boom and an air flow introduced in line with the nozzles (normally, air is extracted at <0.5 m s^{-1}, via the air louvre vents – as shown on the left hand side / back as illustrated – having entered from the top of the unit).

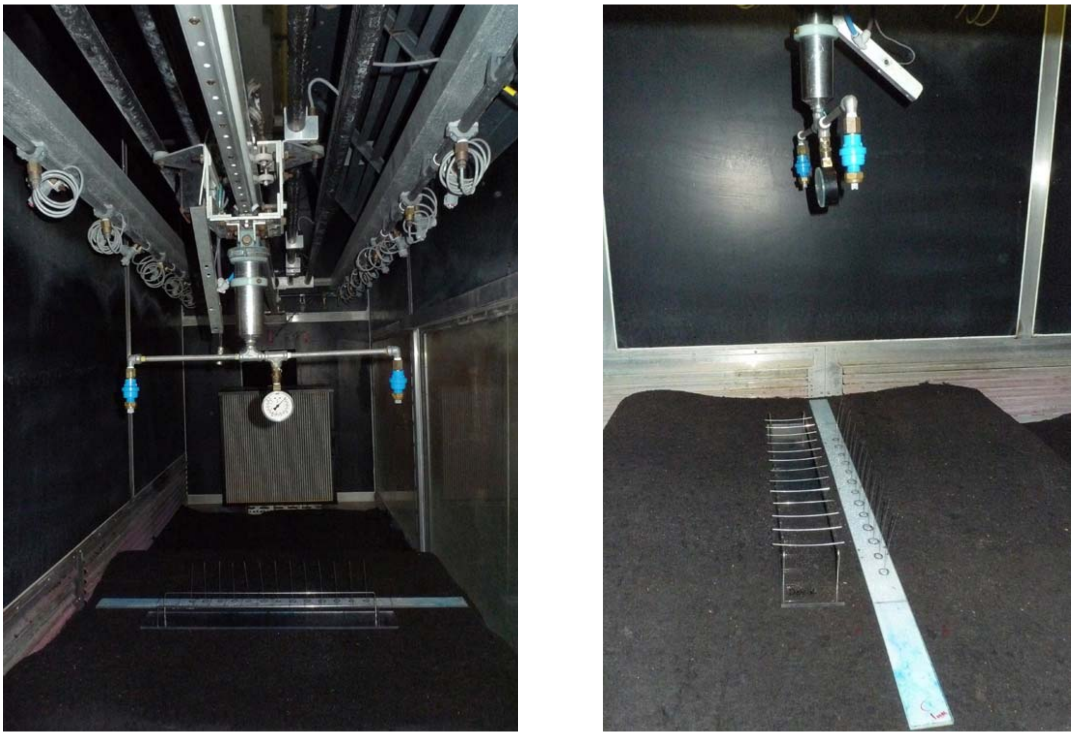


Figure 2. Attempted modification to Mardrive at IPARC: double nozzle, air stream at rear (rejected); right: side view – with targets as configured in all experiments.

Nozzle pressure was controlled using spray management valves (CF Valve, G.A.T.E, Deerfield Beach, Fl, USA.), but these limited pressure options to 100, 150, 200 and 300 KPa (which is also the designed maximum pressure for the whole apparatus). The original plan for achieving a 450 kPa pressure setting was to run the whole Mardrive at this pressure. Unfortunately, this created a number of faults that had to be repaired and furthermore, the introduced air flows were highly complex in the target area (i.e. neither laminar nor defined velocity).

Mardrives are fitted with a number of safety locking devices, some of which were modified and bypassed in the IPARC unit for spray application experiments. Modifications were only made after it had been decided to work only with water/blank, non-toxic formulations recognising that this would be unacceptable in most laboratories where active formulations would be used. There was also a danger of spray splashing on the side walls with two 110° nozzles (as in Figure 2) and therefore a single standard nozzle was used. Having completed a series of preliminary studies it was concluded that there were very limited opportunities for modifying this apparatus (and that other laboratories might not wish to do this) so the Mardrive was used in its standard configuration for subsequent studies.

4.2.5. Measurements in a spray chamber at IPARC – deposits on stainless steel rod targets

A single nozzle travelled at 0.92 m s^{-1} (measured over 2.0 m with a stopwatch, 5 repetitions) and 500 mm above targets (the VAR estimates assume a 500 mm nozzle spacing). Target arrays in a 500 mm swath were sampled with two 13 rod configurations separated by 40 mm: thus both horizontal and vertical targets were positioned with a centre rod and six rods either side, the final one on each side being 240 mm away from the centre line.

The standard formulation used was water plus 0.1% Tween 20 (O'Sullivan *et al.* 2010) with 0.1% (1 g L^{-1}) Green S dye. This was placed in the stainless steel Mardrive formulation cylinder, fitted with a spray management valve and a single nozzle. The dye deposited on rods was washed-off for all 13 rods together in each array and run by agitating for 20 seconds in 10ml of deionised water. The mixture was then placed in 10 x 10 mm square x 45 mm tall cuvettes and measured with a Jenway 6300 visible range Spectrophotometer (Keison Products, Chelmsford, Essex CM1 3UP, UK), which had been calibrated against 5 known dye concentrations.

4.3. Spray drift risk assessment

4.3.1. Field measurements of drift

Field measurements of spray drift were made on two sites using two different arrangements of equipment. On a short cut grass surface at Wrest Park, Silsoe, Bedford a self-propelled 24.0 m boom sprayer was used to make multiple passes upwind of a sampling array that comprised three separate but adjacent rows of samplers with each row containing:

- Sampling frames for collecting airborne spray to a height of 2.0 m that were 1.0 m wide and supported 2.0 mm plastic passive sampling lines mounted horizontally with a vertical spacing of 10.0 cm: these were positioned at 5.0 and 10.0 m downwind of the edge of the treated swath;
- Lathes for supporting chromatography paper strips 50 mm wide and 1.0 m long that sampled sedimenting spray at ground level at distances of 1.0, 2.0, 3.0, 5.0, and 10.0 m downwind of the edge of the treated swath.

Measurements were made with three nozzle conditions that were selected to span the range of likely drift risks as follows:

- A high drift risk case using an "02" 110°conventional flat fan nozzle (FF/110/0.924/4.0 – Hypro EU Ltd) operating at a pressure of 4.0 bar and travelling at a forward speed of 10.0 km/h to apply nominally 110 L ha^{-1};
- A low drift case using a 110° "large droplet" air-induction nozzle (AI/110/1.20/3.0 – TTI Spraying Systems/TeeJet Ltd) operating at a pressure of 3.0 bar and travelling at a speed of 12.0 km/h to apply nominally 120 L ha^{-1};

- A reference spraying condition that used an “03” 110° conventional flat fan nozzle (FF/110/1.2/3.0 – Hypro EU Ltd) operating at a pressure of 3.0 bar and travelling at a speed of 12.0 km/h to apply nominally 120 L ha^{-1}.

Similar measurements were made on a field site in Yorkshire using a 21.0 m trailed sprayer with an equivalent downwind sampling array.

4.3.2. Wind tunnel measurements of drift

Measurements of the airborne spray 5.0 m downwind of a 3 nozzle static boom were made in the wind tunnel on the Silsoe site using a vertical array of 2.0 mm diameter plastic passive line collectors with lines supported at a 10.0 cm vertical spacing. Measurements used two wind speed conditions (mean velocities of 2.0 and 4.0 m s^{-1}) and used a total of five different nozzle configurations as follows:

- A reference “03” 110° conventional flat fan nozzle (FF/110/1.2/3.0 – Hypro EU Ltd) operating at a pressure of 3.0 bar;
- A high drift risk case using an “02” 110° conventional flat fan nozzle (FF/110/0.924/4.0 – Hypro EU Ltd) operating at a pressure of 4.0 bar as in the field trials;
- A low drift case using a 110° “large droplet” air-induction nozzle (AI/110/1.20/3.0 – TTI Spraying Systems/TeeJet Ltd) operating at a pressure of 3.0 bar also as in the field trials;
- A conventional “015” flat fan nozzle (FF/110/0.6/3.0 – Hypro EU Ltd) operating at a pressure of 3.0 bar to examine behaviour at very low flow rates; and
- A low flow rate “015” “large droplet” air-induction nozzle (AI/110/0.6/3.0 – TTI Spraying Systems/TeeJet Ltd) operating at a pressure of 3.0 bar.

5. RESULTS

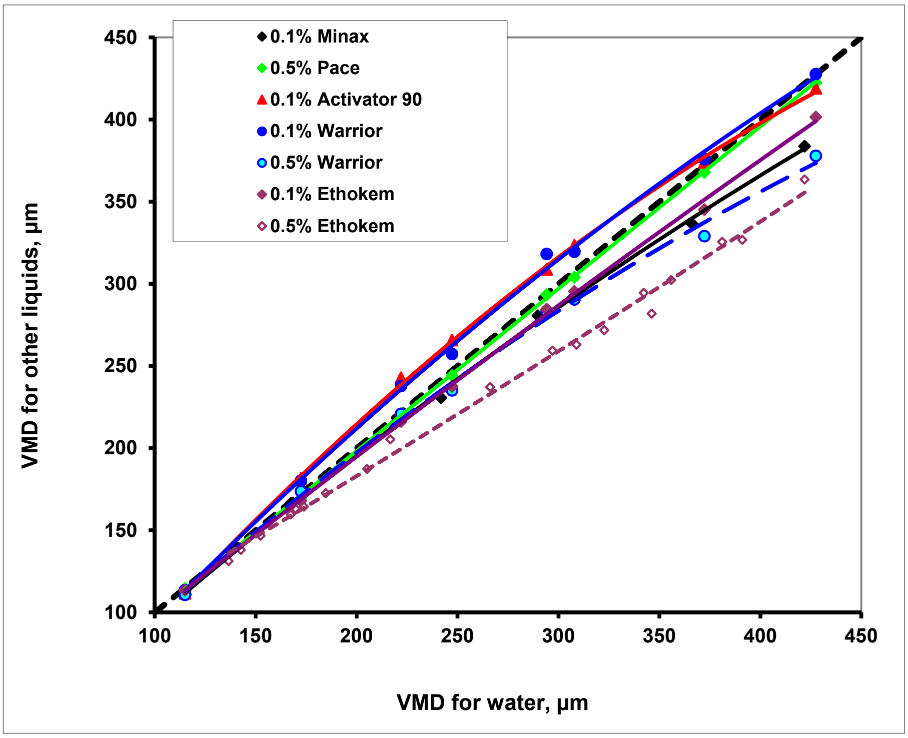
5.1. Defining a test liquid for nozzle performance assessments

5.1.1. Measured droplet size distributions

Measured droplet size distributions with the nozzles listed in Table 1 (Section 4.1.2) operating with water plus a range of commercially available surfactants was plotted. Figure 3 showed that these distributions were different for the different surfactants, particularly for the conventional nozzles generating larger droplet sizes and also for the air-induction nozzles (Note: some additional data from other studies has been added to the plots in Figure 3). The data was plotted as mean droplets sizes expressed as volume median diameters (VMDs). None of these spray liquids gave droplet size distributions that were directly comparable with those when spraying 0.1% Agral with water. It was recognized that selecting a commercially available agricultural adjuvant may have limitations linked to the continuing supply of such a commercial product. The surfactants Tween 20 and

Tween 80 have been used by other laboratories undertaking agricultural crop spraying studies and so further measurements were made with these two surfactants in water and the results are plotted in Figure 4.

The results show good agreement between the droplet sizes for the Tween surfactants compared with Agral for the nozzles used in the study (Table 1). Agreement tended to be slightly better for Tween 80 – for Tween 20 some air-induction nozzles tended to give mean droplet sizes that were less than those when spraying Agral (Figure 4). Other measures of the droplet size distribution such as the percentage of spray volume in droplets <100 μm in diameter also showed good agreement when spraying Agral and the Tween surfactants.



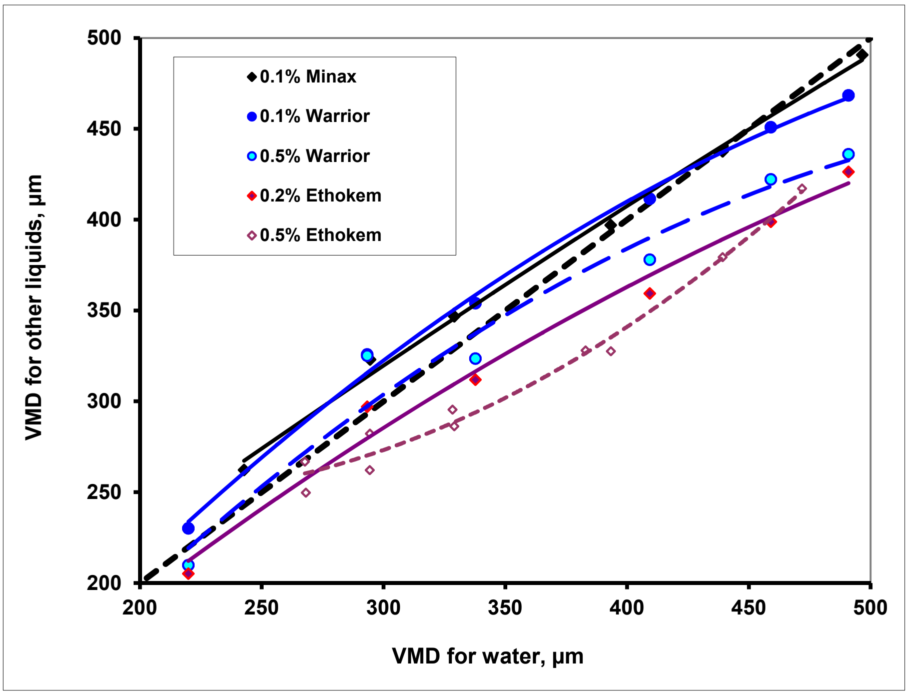


Figure 3. Mean droplet sizes, expressed as volume median diameters, for a range of nozzle types operating to spray different commercially available adjuvant mixtures with water.

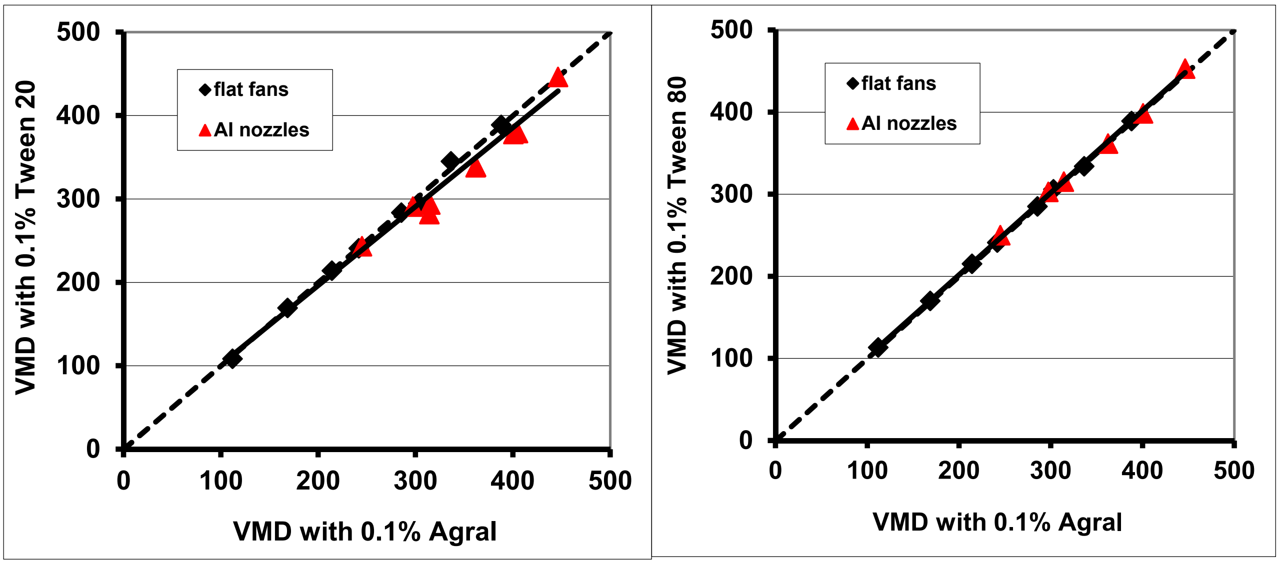


Figure 4. Comparison of mean droplet sizes (as volume median diameter, VMD, μm) when spraying Agral, Tween 20 and Tween 80 at 0.1% in tap water.

5.1.2. Dye recovery and stability

Measurements of the stability of the dye and the Tween surfactant solutions showed no substantial interaction or degradation over a 21 day period when samples were stored in the dark (Figure 5). Liquid stored in ambient lighting conditions did show degradation which was a function of dye concentration. At the lowest concentrations (0.1%), degradation was observed after storing for one day whereas at the higher (0.5% dye) concentration, major degradation occurred after 4 days.

Recoveries from both plastic and paper surfaces were in the range 98 to 108% for both surfactants and showed no change after 15 days storage in dark conditions. Recoveries from the chromatography papers treated with higher volumes of dye and Tween 20 surfactant and stored both when wet and dry, also gave recovery levels of greater than 95%. It was therefore concluded that dyes could be satisfactorily recovered from surfaces sprayed with dye plus Tween surfactant solutions providing that wet samples are not stored in ambient light conditions. It was noted that surfactant solutions were clear when mixed but turned cloudy when stored for more than 24 hours probably due to "autoxidation" (Donbrow *et al*., 1978). It is therefore recommended that liquids are not stored but are freshly mixed for each application.

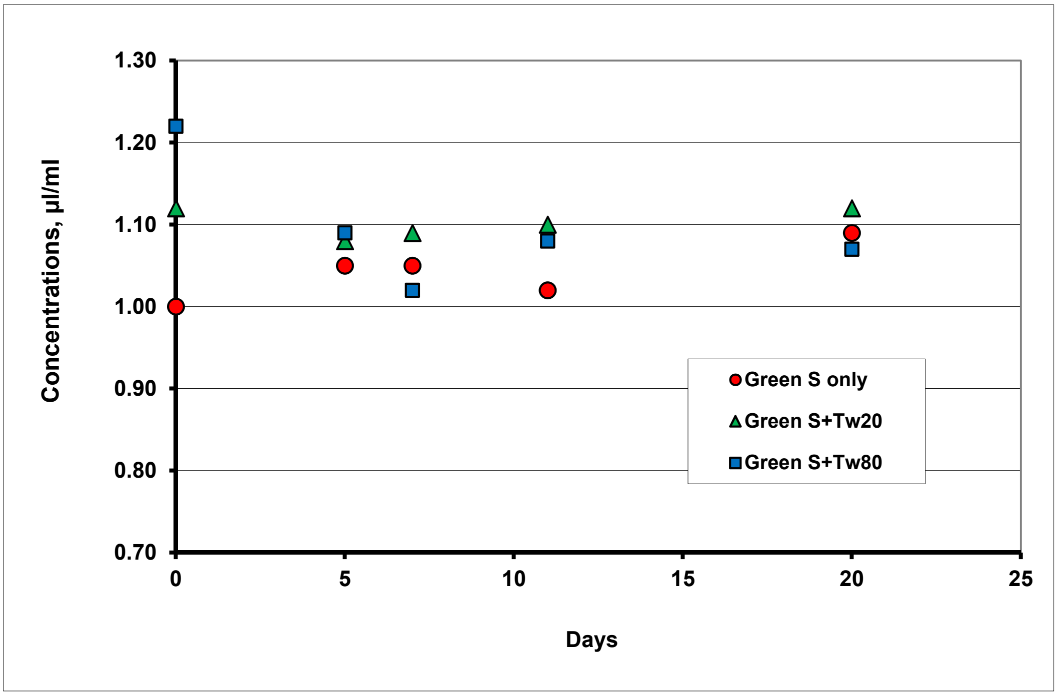


Figure 5. The degradation of Green S with Tween adjuvants in solution during storage (ambient:dark) for 1.0 µl/ml

5.1.3. Other factors relating to the selection of a reference spray liquid

It was noted that Tween 80 was more difficult to measure and mix than Tween 20 and therefore Tween 20 was preferred as a reference surfactant mixed with tap water at 0.1% by volume.

5.2. The measurement of deposit distributions on simplified stainless steel rod targets

5.2.1. Initial measurements of spray deposits in the wind tunnel on the Silsoe site

The distribution of deposit on the vertical 1 mm diameter stainless steel rods sprayed in six replicated tests with two nozzle types in the initial series of tests shown in Figure 6 indicated:

- Consistently higher deposits when applications were made with the conventional flat fan nozzle compared with those when using the large droplet air-induction nozzle: this is contrary to the findings reported by Butler Ellis *et al*., (2008) which used larger targets in still air;
- An approximately uniform distribution across the spray swath particularly when making applications with the large droplet air-induction nozzle: there was some evidence of increased deposits at the edge of the sampled area, corresponding to the mid-point between nozzles, when applications were made with the conventional flat fan nozzle and this may relate to droplet trajectories at this position in the spray.

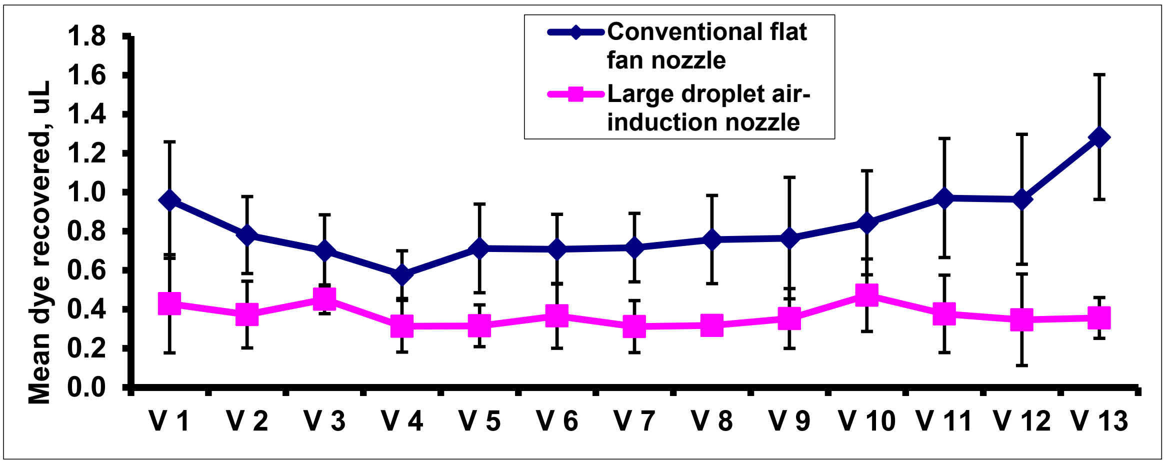
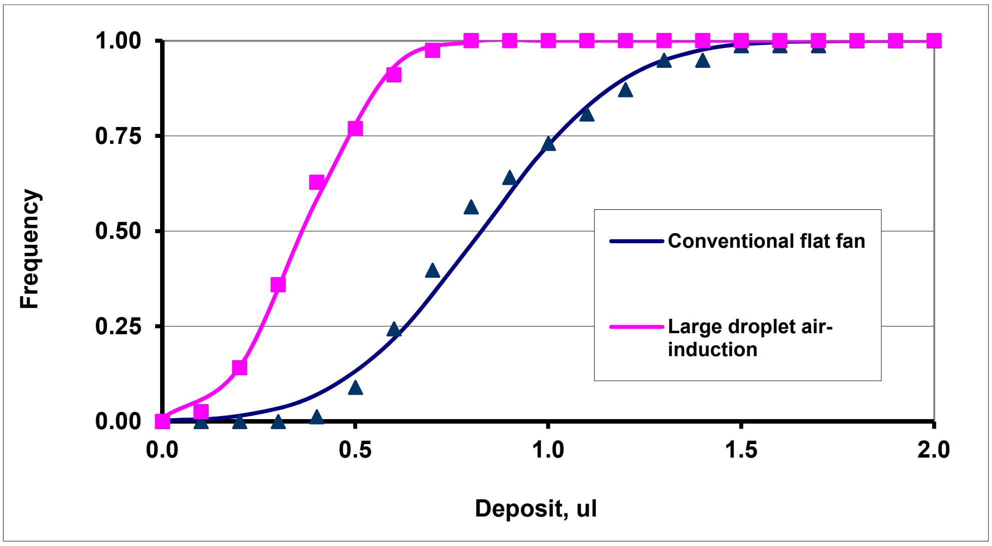


Figure 6. Measured spray deposits on vertical 1.0 mm diameter rods in the central 0.5 m region of a three nozzle boom when applications were made with two nozzle types.

Similar distributions were measured on 2.0 mm diameter stainless steel rods in the same positions and orientation although in this case deposits, when applications were made with the large droplet air-induction nozzle deposits were slightly more variable and the difference between the two nozzle types was much less pronounced. Deposits on both 1.0 and 2.0 mm diameter rods supported horizontally also showed similar patterns with greater deposits when applications were made with the conventional flat fan nozzle particularly with the smaller target size.

Results from the six replicated experiments enabled frequency distributions of the measured deposits to be plotted (Figure 7). These plots confirm that greater deposits were achieved with the conventional flat fan nozzle and that deposits on the rods supported horizontally were greater than in the vertical case, as expected.

The slope of the frequency plot provides an indication of the variability of deposit and it can be seen that for the rods supported vertically, deposits were more variable when applications were made with the conventional nozzle. Equivalent results to those plotted in Figure 7, but when treating 2.0 mm diameter rods, gave results of the same form but with much smaller differences between the two nozzle types although deposits from the conventional flat fan nozzle were still consistently greater than from the large droplet air-induction nozzle.



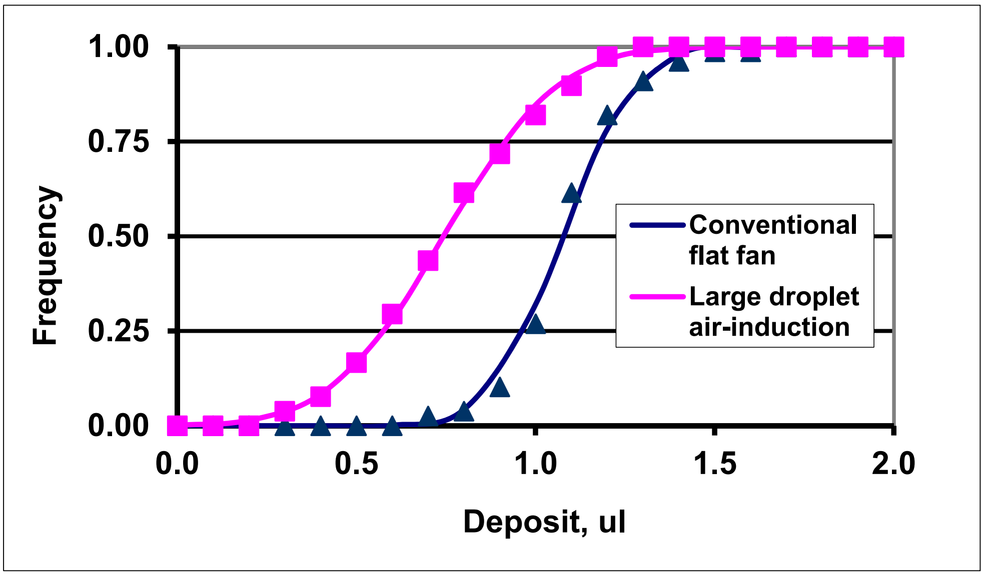


Figure 7. Cumulative frequency plots of the deposits on 1.0 mm diameter stainless steel rods supported vertically (upper graph) and horizontally (lower graph) and sprayed with two nozzle types.

Measurements of deposits on 1.0 mm stainless steel rods when applications were made with a number of nozzle types (Figure 8) showed that both the magnitude and distribution of deposits were mainly a function of droplet size. Consistent trends of decreasing mean deposit with increasing droplet size were recorded.

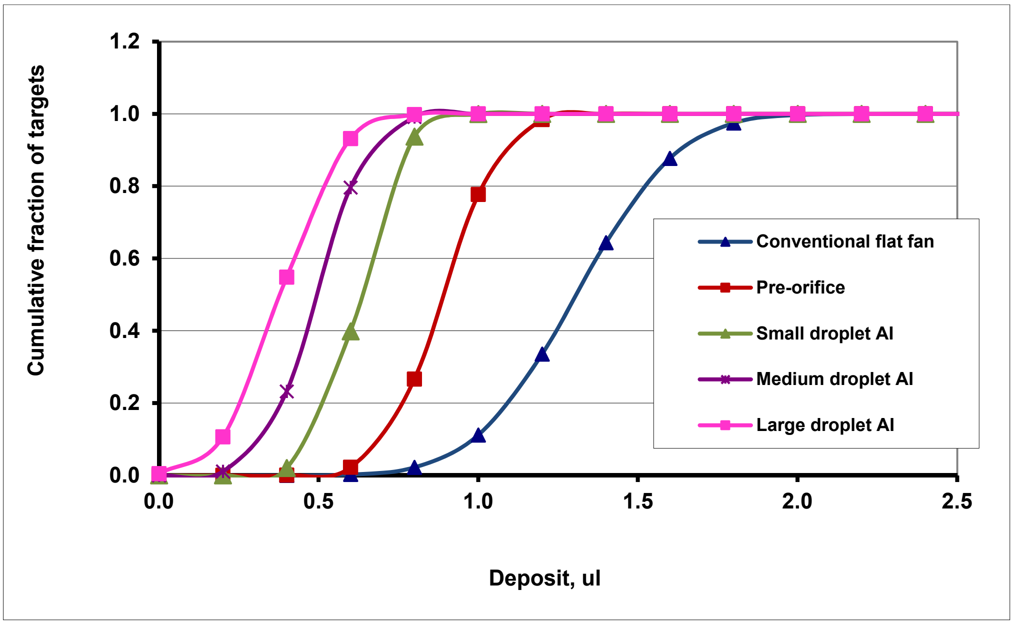


Figure 8. Cumulative frequency distributions of deposits on vertical 1.0 mm stainless steel rods when applications were made with a range of nozzle types.

When the experiment that gave the data plotted in Figure 8 was repeated, the results showed very similar underlying trends but the values for the different nozzle types differed substantially. Variations in the measured deposits could have important implications if such data were to be used as a basis for nozzle/spray classification. The protocol for making such measurements in the wind tunnel on the Silsoe site was therefore reviewed in detail. All spray deposits had been measured in experiments using a low wind speed of 1.0 m s^{-1} and a simulated travelling speed of 10.0 km h^{-1}. It was considered that variations in wind speed may be a factor contributing to the lack of reproducibility in the spray deposit measurements. Direct measurements of wind speed in the tunnel using an ultrasonic anemometer made spatially across the sampling area and over time after the tunnel setting had been re-set showed very little variation in either the mean values or variation of wind speed with time. However, to assess the sensitivity of measured spray deposits to variables defined in the test protocol, it was decided to make measurements of deposits on 1.0 mm stainless steel rods over a range of wind speeds as indicated in Section 4.2.2 above.

5.2.2. The effect of application volume and wind speed on deposits on stainless steel rods – wind tunnel measurements at Silsoe

The effect on spray deposits on vertical and horizontal 1.0 mm diameter rods of varying application volume by using the single, double and triple boom arrangements fitted with conventional flat fan FF/110/0.6/3.0 nozzles and therefore applying 75, 150 and 225 L ha^{-1} (Figure 9) was to give lower normalized deposits at the higher application volumes. This was particularly the case for the vertical rods.

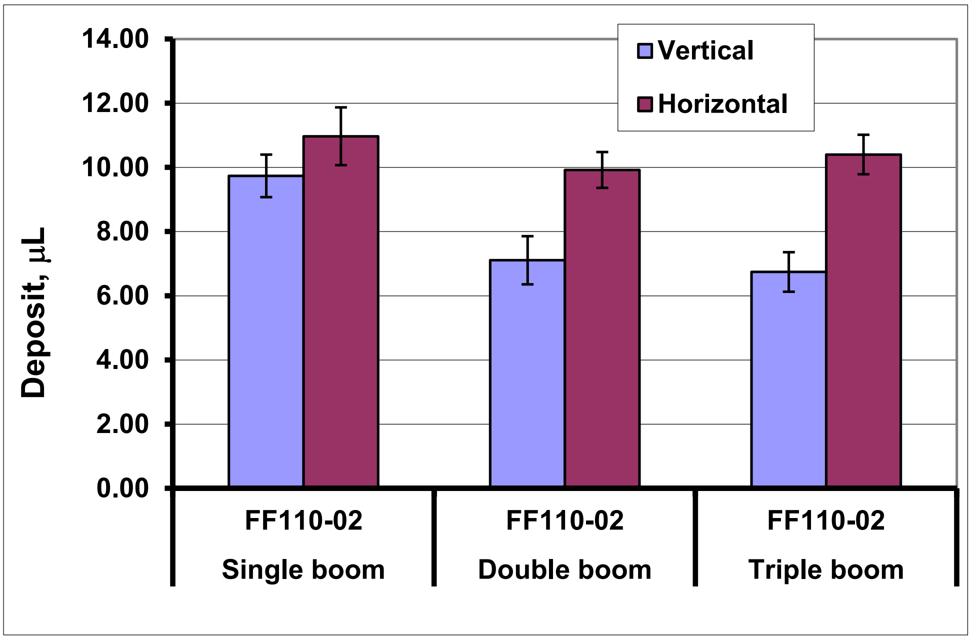
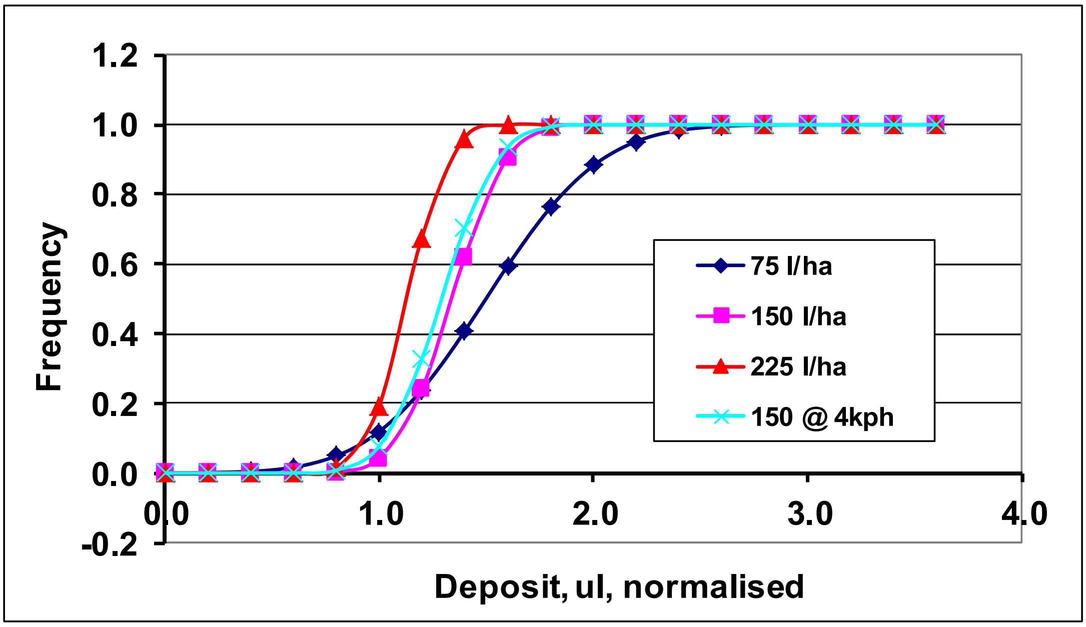


Figure 9. Normalised spray deposits on 1.0 mm diameter stainless steel rods treated with different application volumes using a multiple boom arrangement.

Larger deposits were again recorded on the rods supported horizontally as expected. These findings are in broad agreement with a number of previous studies (e.g. Butler Ellis *et al*., 2008; Butler Ellis *et al*., 2006). Measurements of the cumulative frequency distribution of deposits on the 1.0 mm diameter stainless steel rods shown in Figure 10 confirm the mean trends shown in Figure 9 as expected but also indicate that deposits were more variable at the lower application volumes.



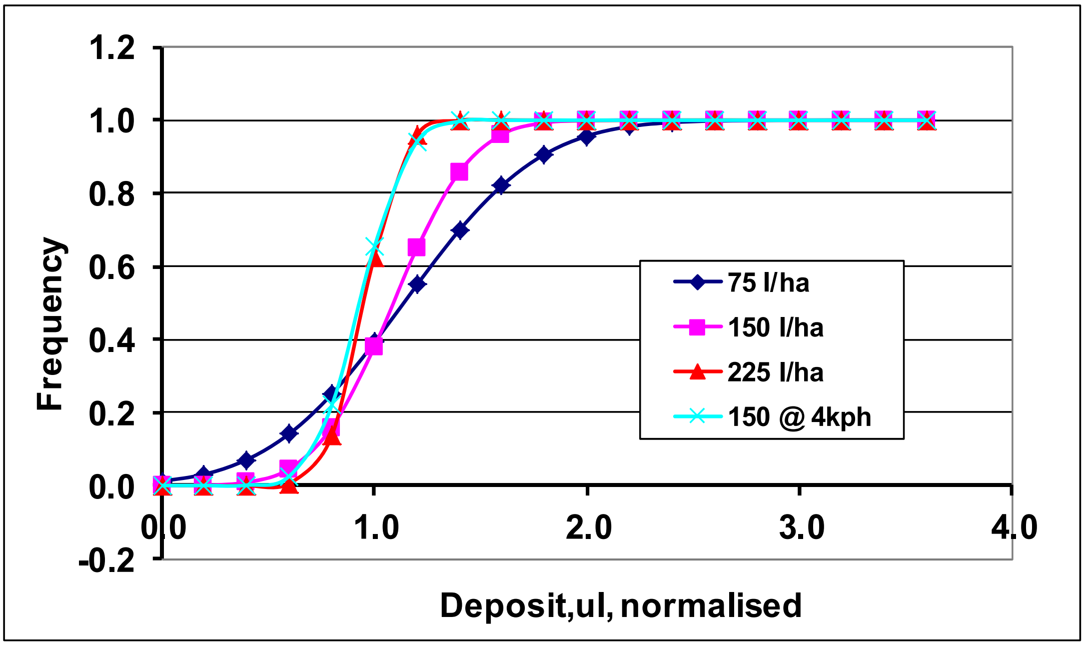


Figure 10. Cumulative frequencies on 1.0 mm diameter stainless steel rods supported vertically (upper) and horizontally (lower) and treated with different application volumes.

The additional treatment of applying 150 L ha^{-1} by reducing the speed of the boom instead of using a double boom gave results that were in reasonable agreement with those when the double boom was used particularly in the case of the rods supported vertically.

The experiments that gave the results presented in Figures 9 and 10 were repeated but were conducted in still air rather than in a mean wind speed of 1.0 m s^{-1}. The cumulative distributions obtained for the 1.0 mm diameter rods supported vertically are shown in Figure 11 together with the moving air results for comparison purposes.

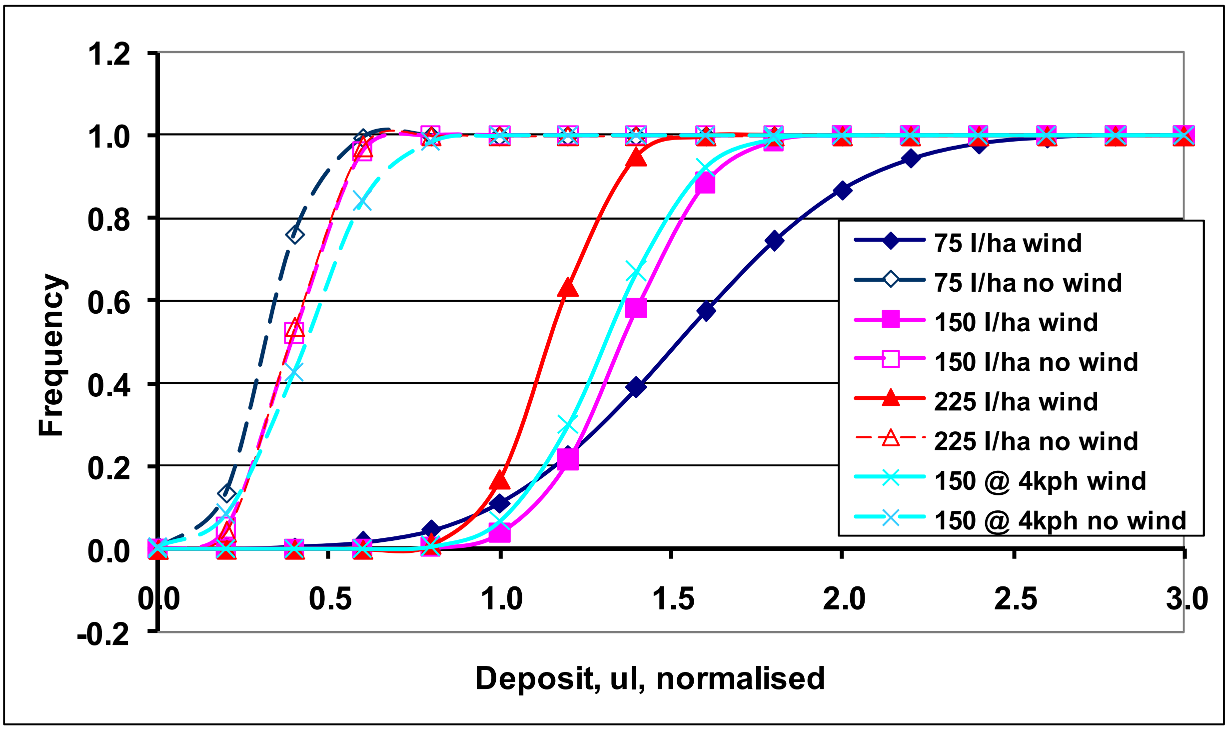


Figure 11. Cumulative frequency distribution of deposits on stainless steel rods supported vertically and treated at different application volumes in two wind speed conditions.

The results plotted in Figure 11 indicate that much lower deposits were consistently measured on the vertical rods in the nominally still air condition when compared with the 1.0 m s^{-1} wind speed case. This is consistent with the effect of wind being to impart some horizontal movement into droplets such that impaction on a small vertical target was increased substantially. The results suggest that the forward motion of the boom has a relatively small effect in imparting a horizontal component of velocity to the spray droplets in comparison with the effect of the air speed between the boom and the target.

Results examining the effect of wind speed on deposits on 1.0 mm diameter stainless steel rods summarized in Figure 12 showed large increases in the deposits on rods mounted vertical and treated with a conventional flat fan nozzle (FF/110/0.8/3.0) as wind speed increased. This result is therefore consistent with those plotted in Figure 11.

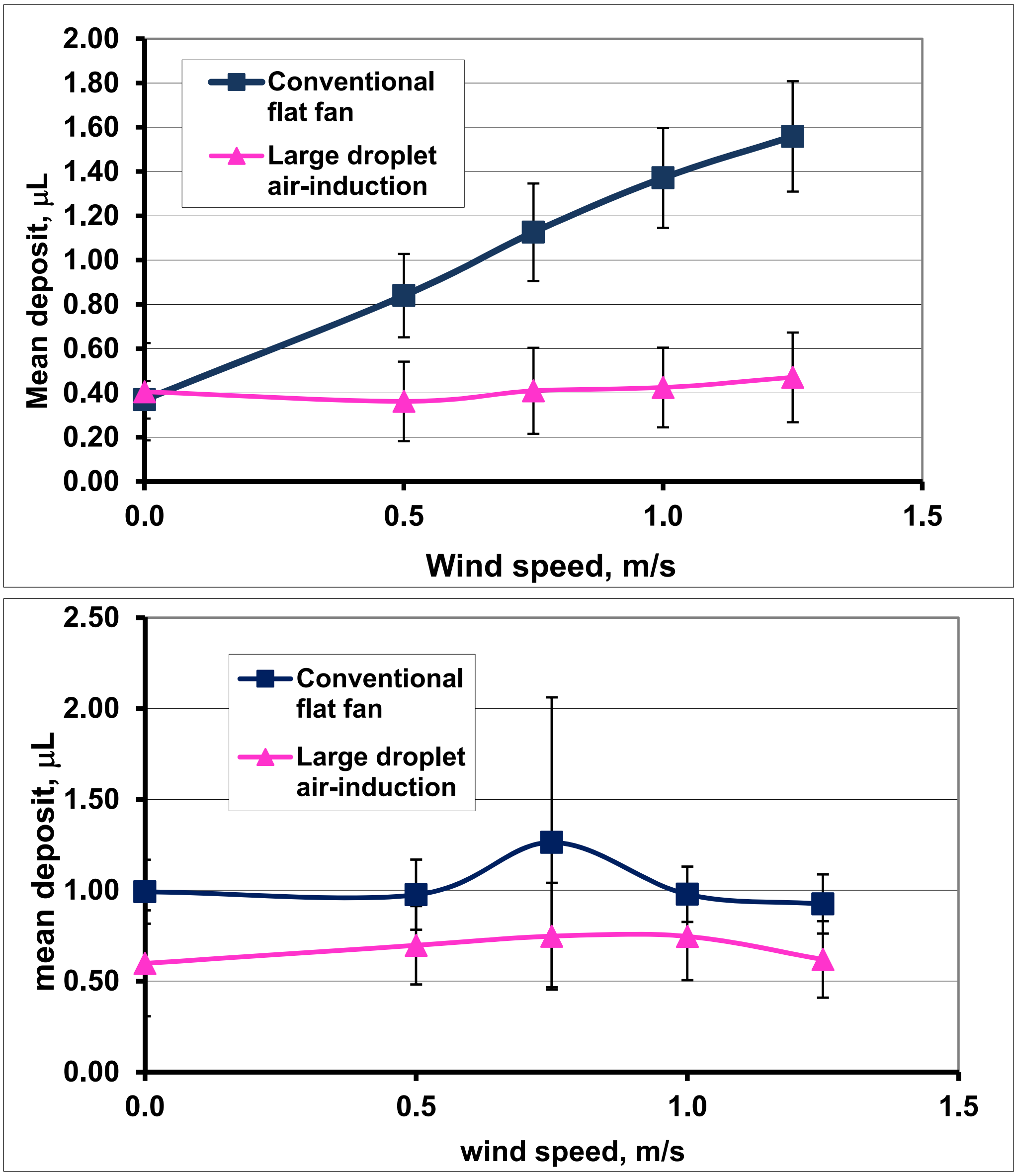


Figure 12. Deposits on 1.0 mm stainless steel rods mounted vertically (upper) and horizontally (lower) and treated in a range of wind speed conditions with two nozzle types.

Deposits on vertical rods treated with the "large droplet" air-induction nozzle (AI/110/0.8/3.0) were relatively independent of wind speed and this result is consistent with this nozzle design giving very low levels of drift. Wind speed values selected for this experiment were relevant to field spraying conditions recognizing that the targets were representative of weeds at ground level and that wind speed varies logarithmically with height above the ground. This means that acceptable wind speed conditions for crop spraying correspond to values of between 0.25 and 0.75 m s^{-1} on the x-axis of the graphs plotted in Figure 12. Deposits on rods supported horizontally showed less consistent variations with wind speed although the magnitude of deposits when sprays were applied with the conventional flat fan nozzle were consistently above those when the "large droplet" air-induction nozzle was used and so were in agreement with the results from previous measurements made as part of this project.

5.2.3. A review of the hypothesis on which the project was based

The initial hypothesis relating to the project was that a measure of potential efficacy with a wide range of products applied from boom sprayers and that could be used in a revised nozzle/spray classification scheme, could be derived from the variability of deposits assessed when treating a defined target matrix with well-defined protocols. This hypothesis was developed based on results from previous studies (Butler Ellis *et al*., 2008) that showed that different application systems gave little difference in mean deposit levels but larger variability with systems using large droplets, particularly the large droplet air-induction nozzle. The results of the experiments conducted in this study using smaller targets are very different. System giving larger droplets gave lower deposits on the small targets. High levels of variability were also associated with low application volumes and the use of conventional flat fan nozzles. These conditions do not map directly to field conditions that would be expected to give low levels of efficacy (Butler Ellis *et al*., 2006 and 2008) and therefore the initial hypothesis was not supported by the data collected.

The magnitude of deposits, particularly on small targets was a function of target orientation, nozzle type and wind speed. Reducing application volumes had again been shown to increase the magnitude of deposits and this would also be expected to influence product efficacy particularly when applying active substances that do not have a major contact mode of action.

A further series of deposit measurements were made in which particular attention was paid to the details of the protocol with the aim of matching the results to measures of droplet size and velocity as presented in Section 4.2.3 of this report.

5.2.4. Measurements of deposit on stainless steel rods with different nozzle designs – measurements at Silsoe (Series 2)

This second series of spray deposit measurements used a lower mean wind speed in the tunnel (0.5 m/s uniformly across the tunnel section) and an array of 1.0 mm stainless steel rods comprising:

- Three rows each of 12 rods supported vertically with deposits determined for the bulk of rods rather than rods individually;
- One row of 12 rods supported horizontally with deposits again measured for the bulked sample of rods.

Applications were made with the nozzles listed in Table 2 (Section 4.2.3) and the resulting mean normalized deposits are plotted in Figure 13.

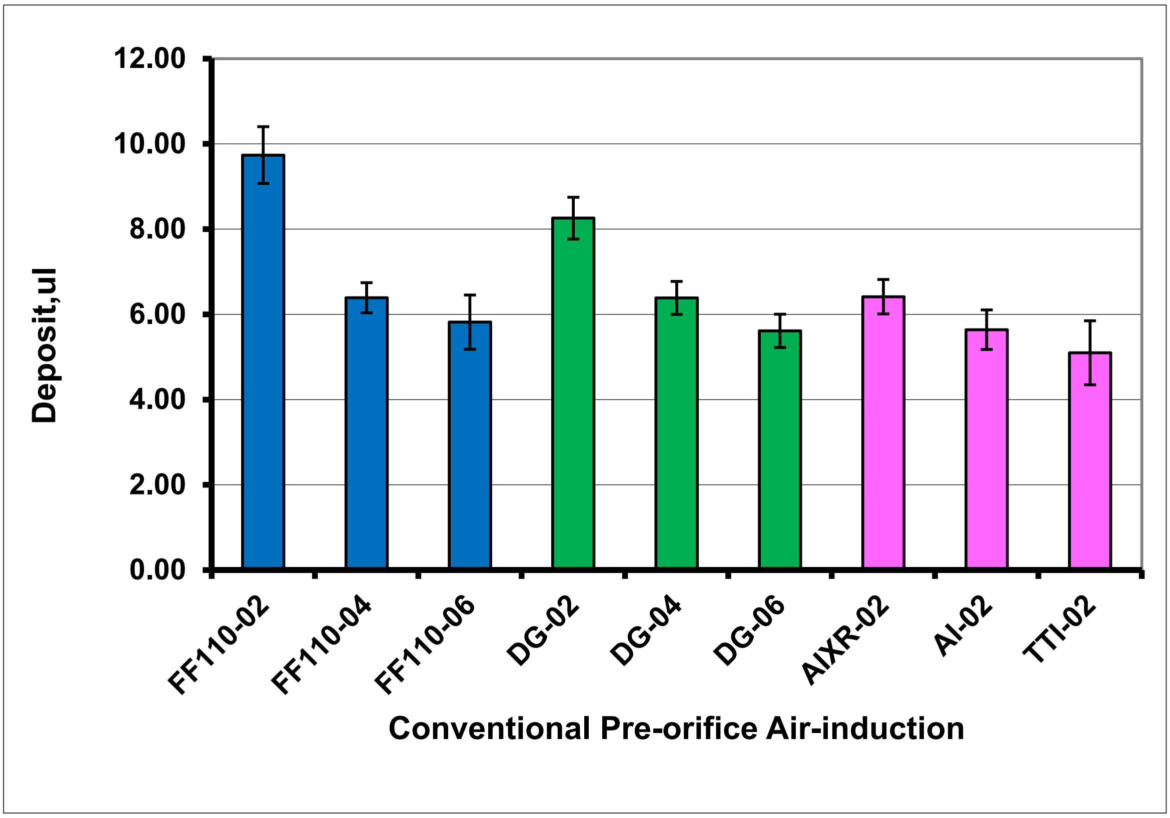


Figure 13. Mean normalized deposits measured on 1.0 mm stainless steel rods supported vertically and treated with a range of nozzle types.

Relating the deposits in Figure 13 to the measured droplet sizes gave the relationships plotted in Figure 14 for vertical targets and Figure 15 for horizontal targets. While these results have been presented in terms of a constant applied dose, no other corrections have been made. The slope of line representing deposits with increasing droplet size therefore has a component relating to the effect of increasing applied volume for the conventional and pre-orifice nozzles as indicated in Figure 9. All of the air-induction nozzles had the same flow rate and therefore for this nozzle design there are no flow rate effects in the plots shown in Figures 14 and 15.

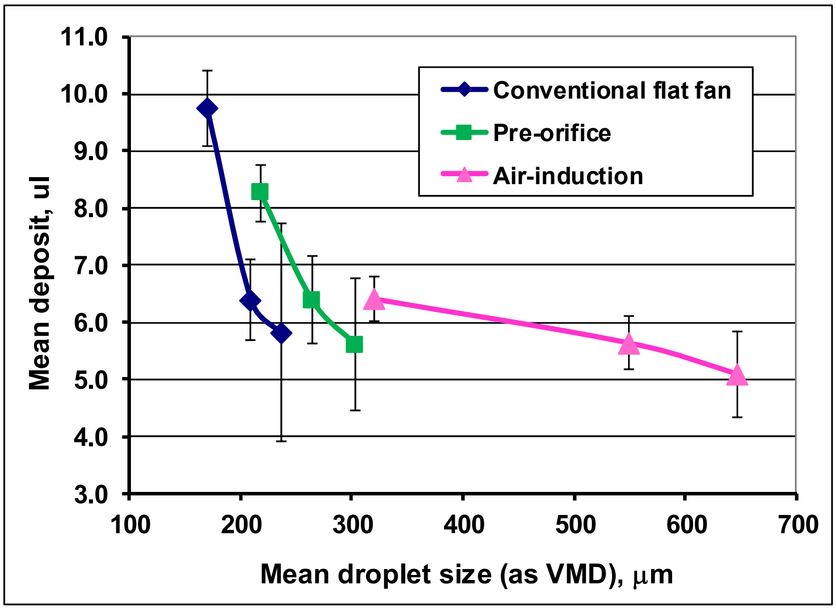


Figure 14. Mean deposits on 1.0 mm diameter stainless steel rods supported vertically plotted against measured mean droplet size in the spray.

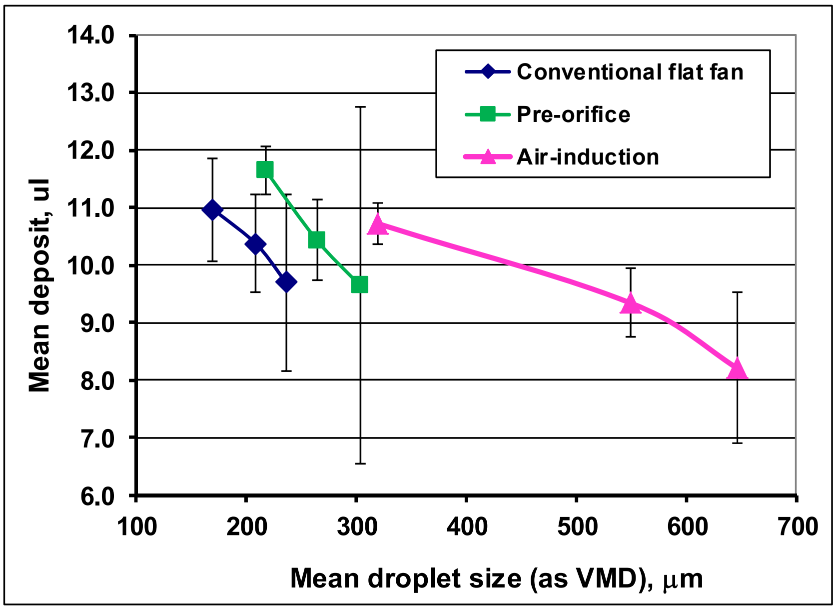


Figure 15. Mean deposits on 1.0 mm diameter stainless steel rods supported horizontally plotted against measured mean droplet size in the spray.

In Figure 16, the values for the rods supported horizontally shown in Figure 15 have been fitted with linear regression lines and values marked corresponding to the droplet sizes of the existing reference nozzles defining the fine/medium and medium/coarse spray quality boundaries. This indicated that there may be some scope for using spray deposits to provide a classification parameter representing likely efficacy but that data was needed over a wider range of droplet sizes for the different nozzle designs in order to explore this potential further.

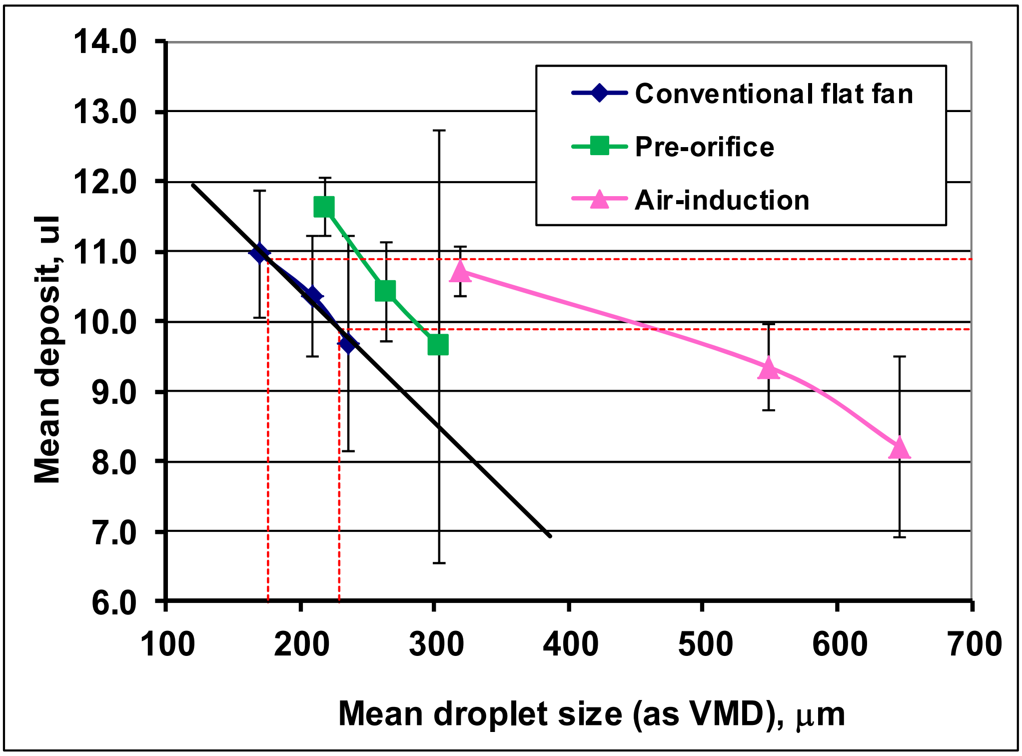


Figure 16. Mean deposits on 1.0 mm diameter stainless steel rods supported horizontally plotted against measured mean droplet size in the spray – also showing the values of droplet size for the fine/medium and medium/coarse boundaries in the existing scheme.

A further set of deposit and droplet size distribution measurements (Series 3) were made using the same nozzles as in Series 2 reported in Figures 14, 15 and 16, but with additional conventional nozzles included that represented the boundary nozzles in the existing BCPC nozzle classification scheme. All of the results from the three series of measurements relating to deposits on vertical and horizontal 1.0 mm diameter stainless steel rods are summarised in Figure 17. While distinct groups of deposits can be readily identified, particularly for deposits on rods treated with air-induction nozzles, the results do show considerable variability. Some of this variability can be explained by the difference in wind speed conditions with a higher speed (1.0 m s^{-1}) used in the initial experiments and lower speed (0.5 m s^{-1}) used for both Series 2 and 3. For the larger droplet sizes with both conventional and air-induction nozzles, the differences between deposits on rods supported vertically and horizontally were consistent with higher deposits on the rods supported horizontally. With the smaller droplet sizes from the conventional nozzles, deposits tended to be more variable and the differences between deposits on the rods in the two orientations were less pronounced.

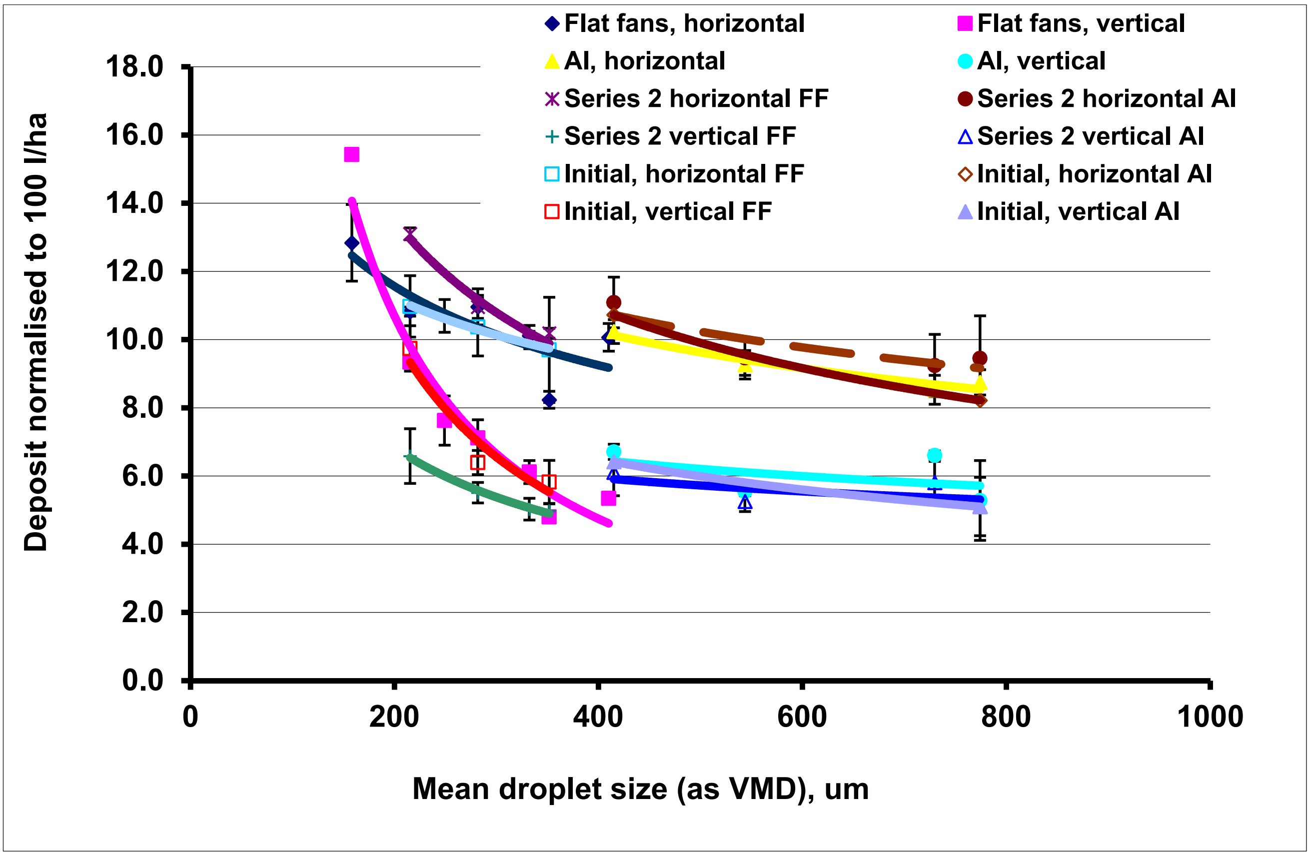


Figure 17. Summary of measured deposits on 1.0 mm diameter stainless steel rods treated with conventional flat fan and air-induction nozzles – measurements at the Silsoe site.

5.2.5. Measurements of deposit on stainless steel rods with different nozzle designs – measurements at IPARC

Results from the experiments conducted in the "Mardrive" chamber at IPARC summarised in Figure 18 and plotted as a deposit per unit emission from the nozzles (DUE) against droplet sizes measured, with a Malvern analyser show the same trends as recorded in the wind tunnel at Silsoe. The agreement between the form of the results plotted in Figures 17 and 18 indicates that if a protocol for measuring deposits on a defined target matrix was defined, then this could be adapted for use in a range of conditions and would not necessarily require the same facilities for both droplet size measurement and spray deposits in controlled conditions that are available on the Silsoe site.

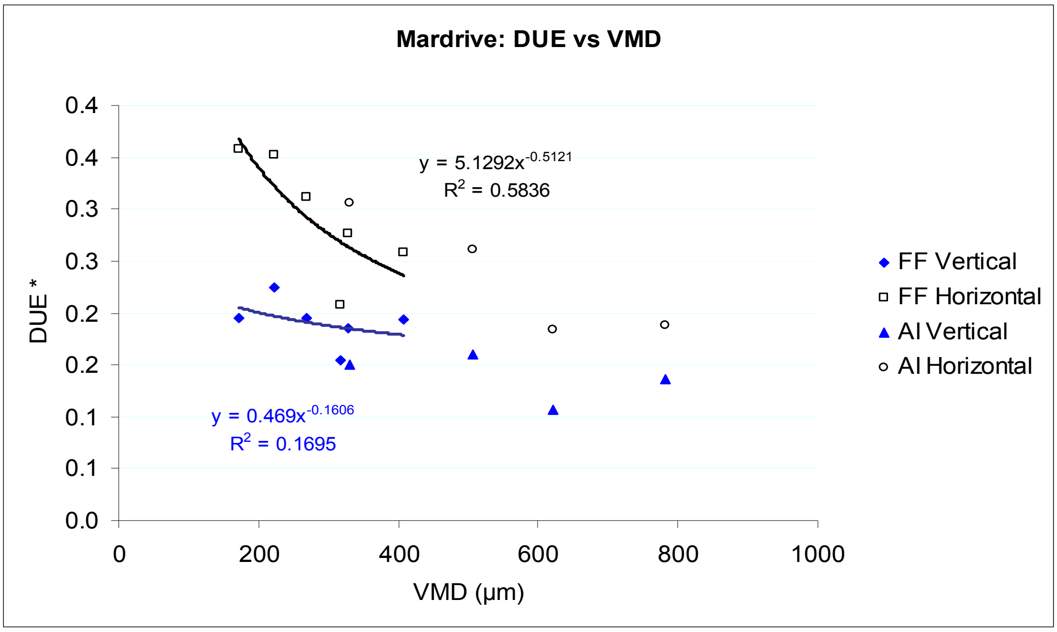


Figure 18. Summary of measured deposits on 1.0 mm diameter stainless steel rods treated with conventional flat fan and air-induction nozzles – measurements at the IPARC site.

5.3. Spray drift measurements

5.3.1. Field trials

Results from field trials conducted on the Silsoe site (Figures 19 and 20) as ground deposits and airborne spray fluxes, respectively, show the expected trends, although the levels of drift deposit from the high drift case ("02" flat fan nozzle at a pressure of 4.0 bar) were not substantially greater than for the reference condition ("03" nozzle at 3.0 bar pressure). Much lower drift deposits and airborne spray volumes were measured with the "large droplet" air-induction (TTI) nozzle as expected. Ground drift deposits (Figure 19) showed the expected decrease with increasing distance downwind from the edge of the treated swath and lower airborne spray volumes were measured at 10.0 m downwind than at 5.0 m, also as expected. Airborne deposits (Figure 20) were also lower at 10.0 m downwind than at 5.0 m as expected although in this case, higher deposits were measured at the 5.0 m distance with the reference system than with the high drift case. Wind speeds for the eight sets of runs measured at a height of 2.0 m varied between 3.6 and 4.6 m/s with no consistent trends over the treatments conducted. The results plotted in Figures 19 and 20 are given in terms of a volume of original spray liquid collected on the sampling matrix for each system but corrected for the different nozzle outputs.

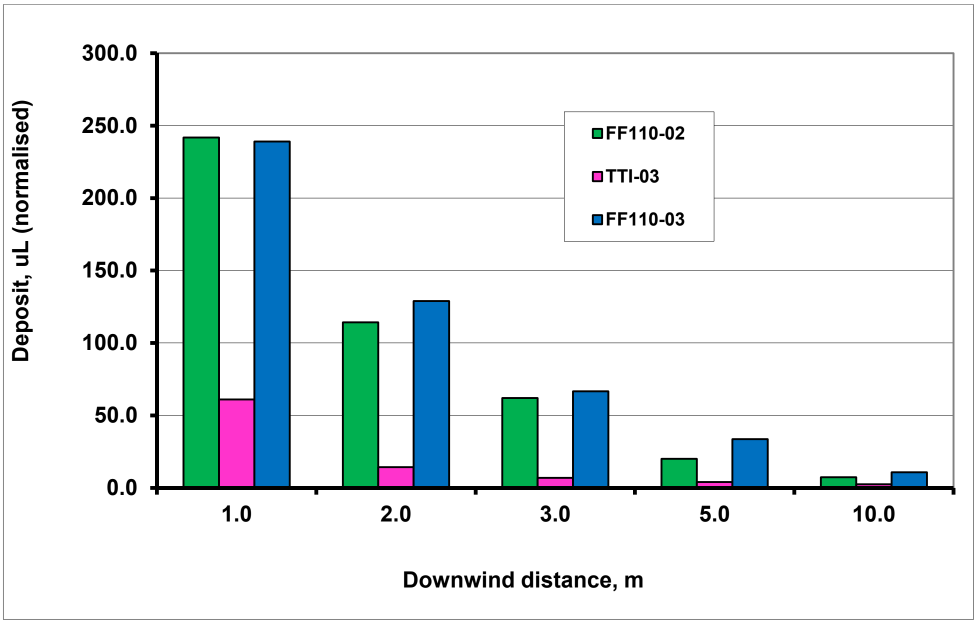


Figure 19. Measured ground deposits at different distances from the edge of the sprayed swath in spray drift experiments conducted on the Silsoe site. Results are the mean values from two experimental runs each using three measurements at each sampling distance.

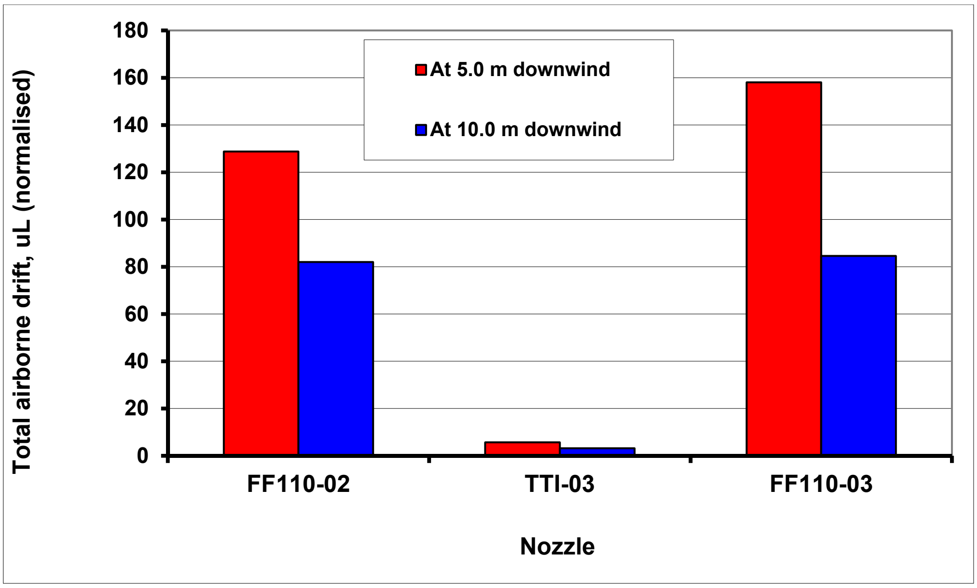


Figure 20. Measured airborne spray deposits at two distances from the edge of the sprayed swath in spray drift experiments conducted on the Silsoe site.

The definition of a drift parameter for inclusion in a classification system is likely to relate to relative drift values and therefore it is the forms of the relationships shown in Figures 19 and 20 that are relevant.

Results of ground drift deposits from experiments conducted in Yorkshire (Figure 21) showed very similar patterns to those recorded on the Silsoe site with deposits from the reference FF/110/1.2/3.0 ("03") nozzle tending to be slightly higher than those from the high drift risk FF/110/0.92/4.0 ("02"). Deposits from the large droplet air-induction nozzle were again much lower as expected with the relative proportions similar to those found in the experiments on the Silsoe site. Results plotted in Figure 21 are in terms of a percentage of the applied dose but, as above, it is the relative magnitudes that are important.

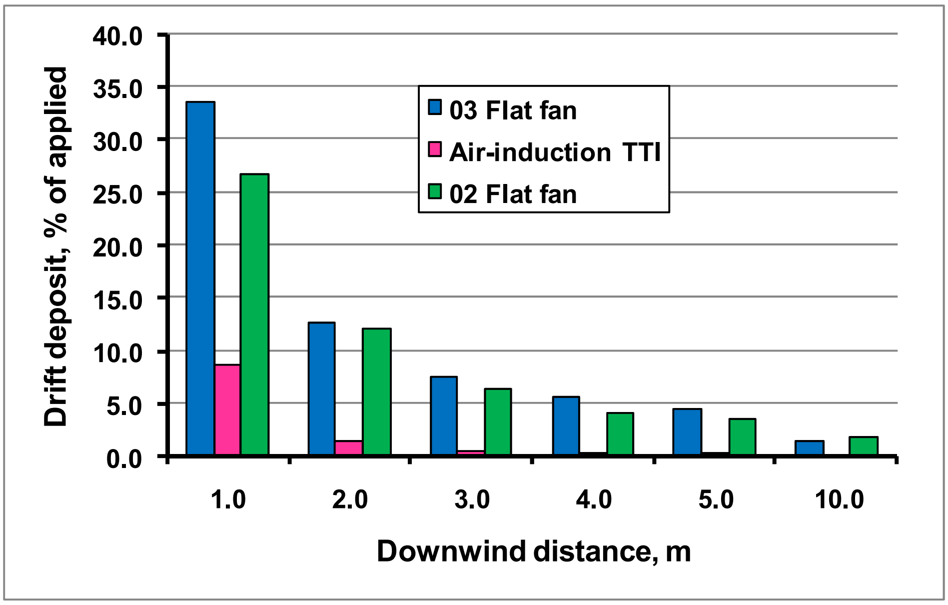


Figure 21. Measured ground deposits at different distances from the edge of the sprayed swath in spray drift experiments conducted on the Yorkshire site. Results are the mean values from two experimental runs each using three measurements at each sampling distance.

5.3.2. Wind tunnel studies

The first series of wind tunnel experiment explored further the definition of the high drift case, particularly given that the results from the field tests had not shown substantially higher levels of drift from the "02" flat fan nozzle at a pressure of 4.0 bar compared with the reference "03" nozzle at 3.0 bar pressure. Results of airborne spray profiles measured 5.0 m downwind of a 3 nozzle boom (Figure 22) show the expected form of deposits with sampling height with the highest volumes at the lowest heights. The relative magnitudes of deposits were also in line with expectations with the highest level of airborne deposits measured with the smallest nozzle size generating the finest spray quality. The total airborne spray volumes plotted in Figure 23 show the summed volumes that are plotted in Figure 22 and confirm the expected relative airborne spray volumes. A wind speed in the tunnel of 2.0 m/s was used for these measurements with the nozzle mounted at a height of 0.6 m, i.e. 0.5 m above the lowest measuring line and consistent with protocols used for obtaining data in support of LERAP star ratings.

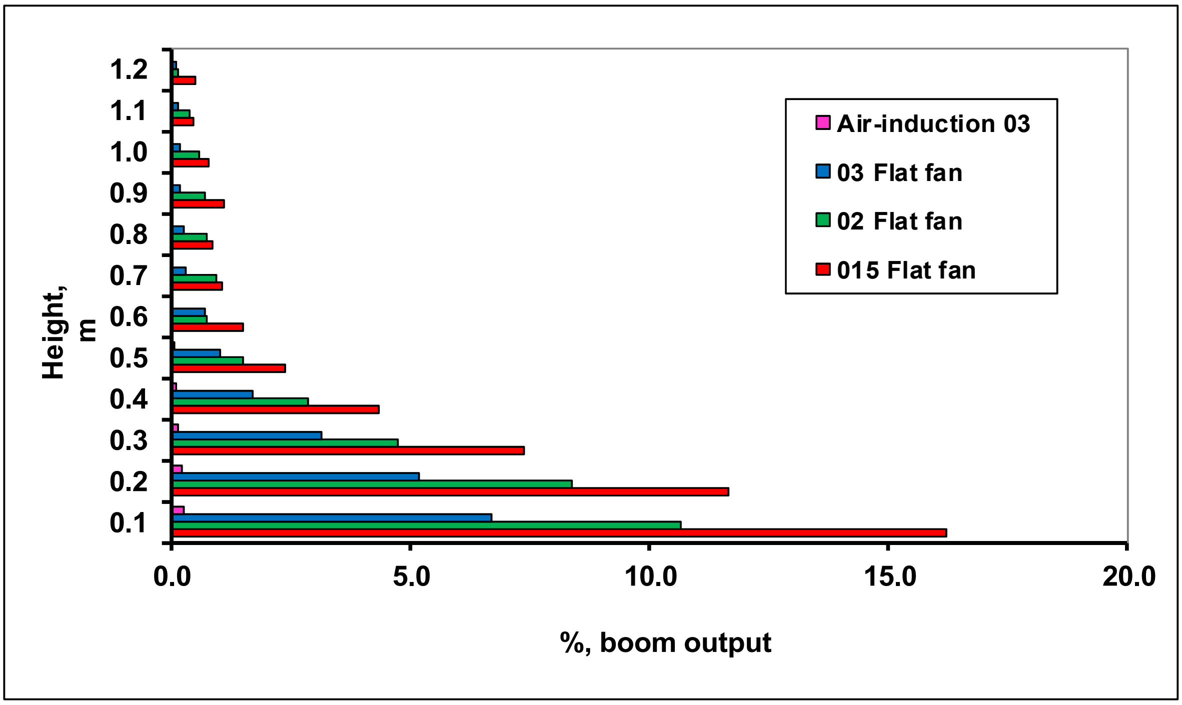


Figure 22. Airborne spray profiles measured in wind tunnel tests

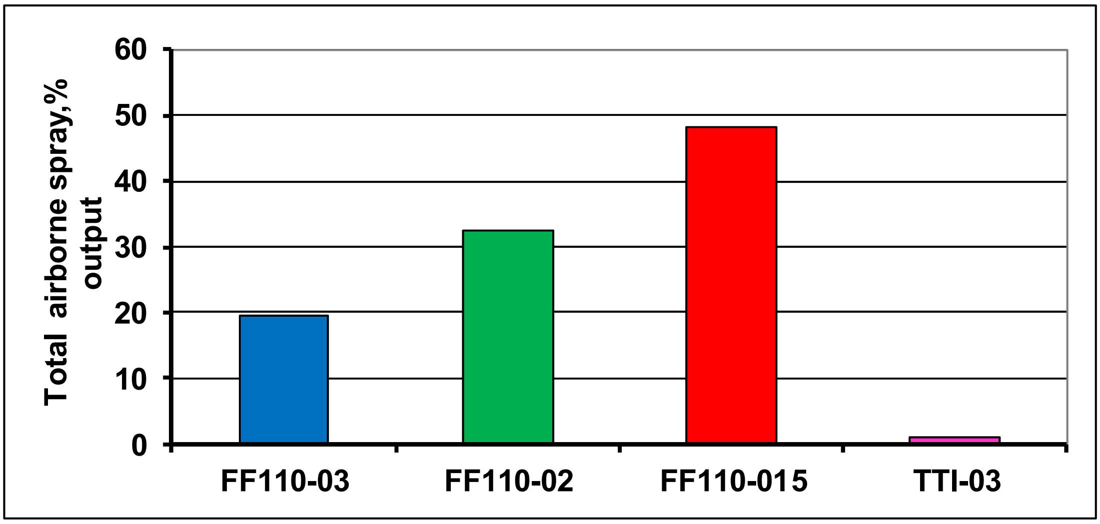


Figure 23. Total airborne spray volumes measured in wind tunnel tests

It is noticeable from the results in Figure 22 that spray drift was sampled at heights above that of the boom for all the nozzles used even though air flow conditions in the tunnel are constrained compared with those in field conditions.

A second series of experiments used the same arrangement to explore the effect of wind speed in the tunnel. For these measurements, nozzles were mounted 0.5 m above the floor of the tunnel and the sampling matrix of passive line collectors supported horizontally with the lowest line 0.1 m from the floor as in the previous runs. Results showed that increasing wind speed increased the quantity of airborne spray downwind of the boom (Figure 24), as expected, and the differences in drift between the conventional flat fan and air-induction nozzles were again maintained. Results plotted in Figure 24 are again expressed as a volume of original spray liquid but have been normalized to correct for differences in nozzle output.

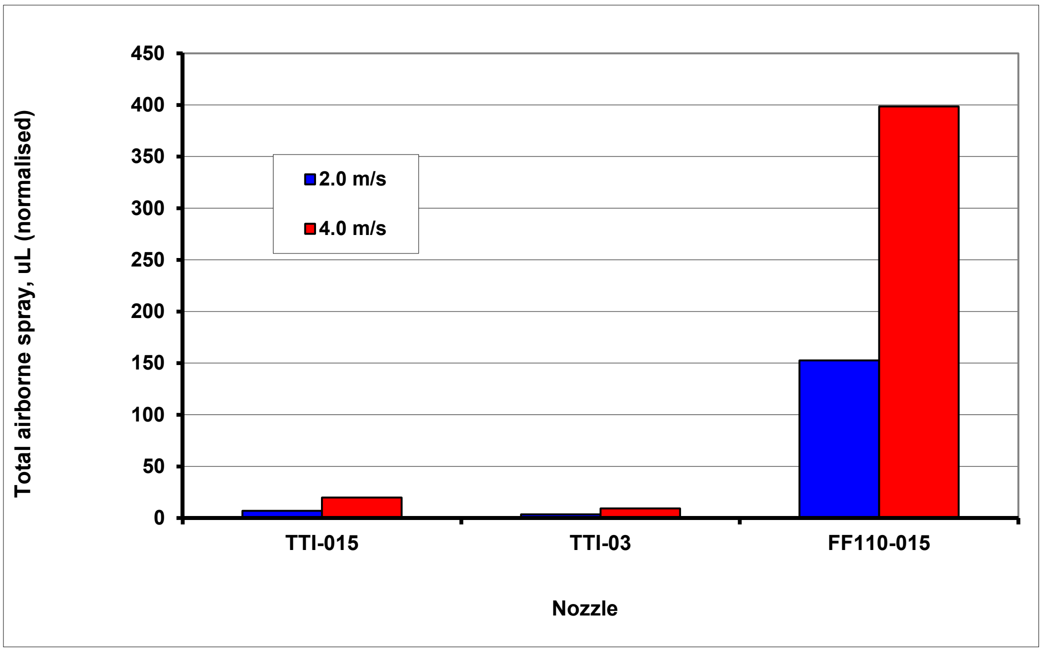


Figure 24. Total airborne spray measured in wind tunnel tests with different nozzles and at two wind speeds.

Results for the two sizes of large droplet air-induction nozzle show that the smaller nozzle size gave slightly higher airborne spray volumes as expected.

6. DISCUSSION

6.1. Relating to the measurements of deposit distributions and the potential to define an indicator of efficacy within an extended spray classification scheme

The original nozzle/spray classification scheme that used measurements of the droplet size distribution to determine a spray quality classification (Doble *et al.*, 1985) had implied links to spray deposition, likely product efficacy in a wide range of situations and the risk of drift. The development and widespread adoption of application systems that generate air-included sprays (air-induction and twin-fluid nozzles) resulted in a situation whereby there was evidence that the measurement of droplet sizes alone was not an adequate approach to spray/nozzle classification in relation to likely product efficacy (Butler Ellis *et al*., 2008). The results obtained in this study confirmed that deposition of sprays having air-inclusions was greater than would have been expected based on the extrapolation of data obtained with conventional nozzle designs giving larger droplet sizes. The results therefore support the approach taken in the AHDB Cereals & Oilseeds Nozzle Guide (2010) in which the performance of sprays from air-induction nozzles were rated differently from that of conventional and/or extended range/variable pressure nozzles and in which sprays from such nozzles were regarded as either “small droplet” or “large droplet” air-induction nozzles. However, the hypothesis that measures of the variability of spray deposits on a defined target matrix and obtained using defined protocols was not supported, because many situations that gave high deposit variability were known to give high levels of efficacy when treating combinable crops in typical field conditions and with a range of product types. Measurements of the magnitude of deposits were not sufficiently consistent and repeatable to give the resolution likely to be required for an appropriate nozzle/spray classification scheme.

Spray and droplet behaviour is a function of velocity (involving both speed and direction/trajectory) as well as droplet size. Previous work based on Dimensional Analysis (Lake and Marchant, 1983) had suggested that the deposition of sprays was a function of a parameter that included size, density and velocity ($\rho U/D^{0.29}$ where ρ is the droplet density, U is the velocity and D is the diameter) and therefore the analysis of the results was reviewed to determine if considerations of droplet velocity and impact energy at the target surface would improve the potential for the classification of sprays from a range of nozzle types. The results in Figure 25 show the measured cumulative percentage of spray volume/velocity correlations for four different nozzle types used in the study. These measurements were made at a height that was 0.5 m below the nozzle corresponding to the target positions used in the deposit experiments and such that droplets, particularly at the smaller end of the size distribution, would have slowed from the initial velocities when leaving the nozzle. As expected, the highest velocities were recorded for the conventional flat fan nozzle having the largest flow rates while the lowest velocities were from the conventional “02” nozzle because of the higher proportion of spray volume in small droplets from this nozzle. The air-induction nozzle gave correlations between those of the two sizes of conventional flat fan nozzle reflecting the larger droplet sizes and lower initial velocities from this nozzle’s design. Results for the pre-orifice nozzle design gave velocities that were close to those of the larger (‘06’) size of conventional nozzle and again reflect the larger sizes of droplets produced by this nozzle.

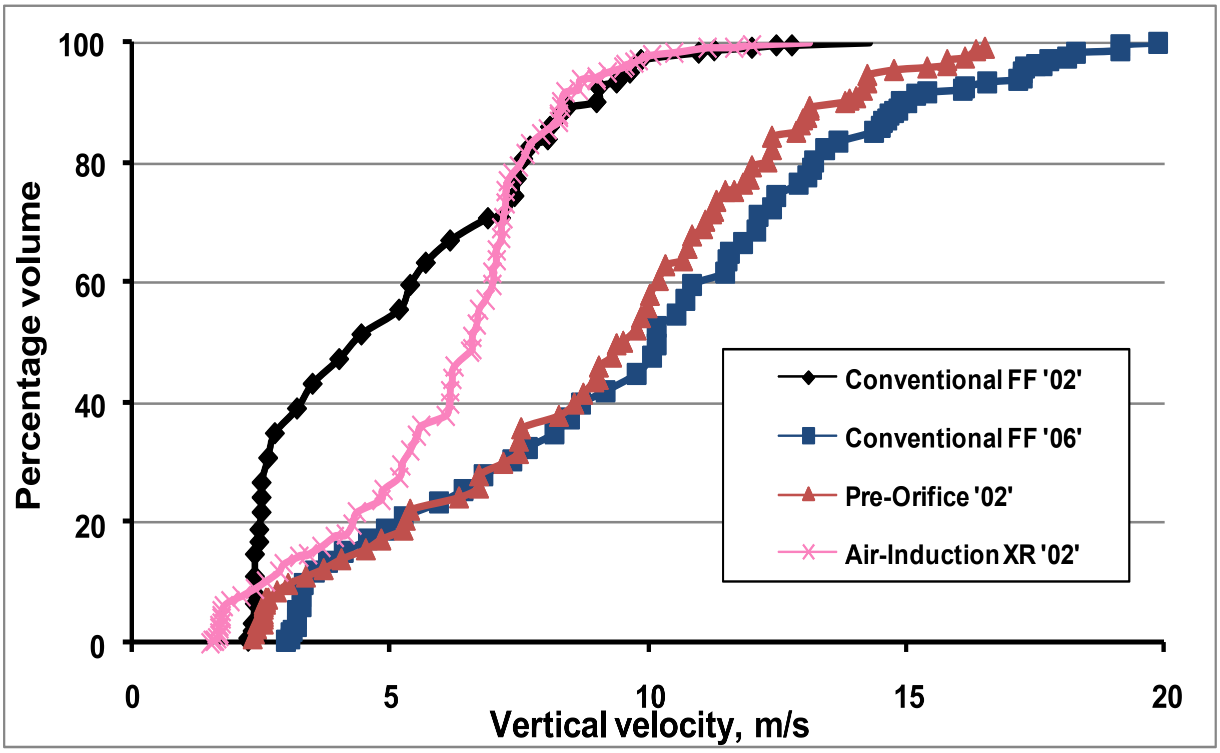


Figure 25. Measured percentage of spray volume/velocity correlations for four of the nozzles used in the study.

Comparing the measured droplet velocities plotted in Figure 25 with measured deposits shown in Figures 13,14 and 15 indicates that the droplet velocities do correspond to deposits for the smaller conventional '02', the air-induction and the large '06' conventional nozzle (lower velocities relating to higher deposits) but do not correctly indicate the higher deposits measured with the pre-orifice nozzle.

The data in Figure 25 was then used to plot the □U/$D^{0.29}$ parameter and a measure of impact energy (proportional to □.U^2.D^3) in Figures 26 and 27, respectively. The relationships plotted in Figure 27 shows that the calculated impact energy does not correlate with relative deposits measured on vertical or horizontal targets as the values for much of the spray volume did not substantially discriminate between the large conventional nozzle, the pre-orifice nozzle design or the air-induction nozzle.

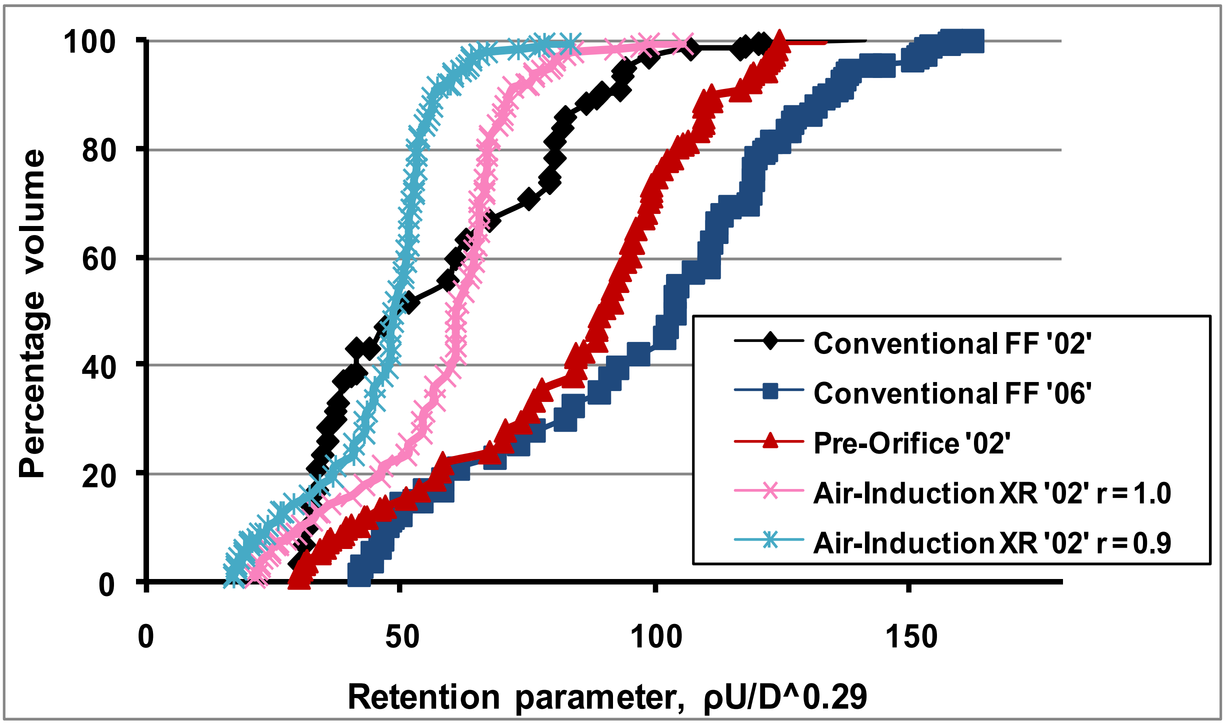


Figure 26. Measured percentage of spray volume □U/D$^{0.29}$ correlations for four of the nozzles used in the study.

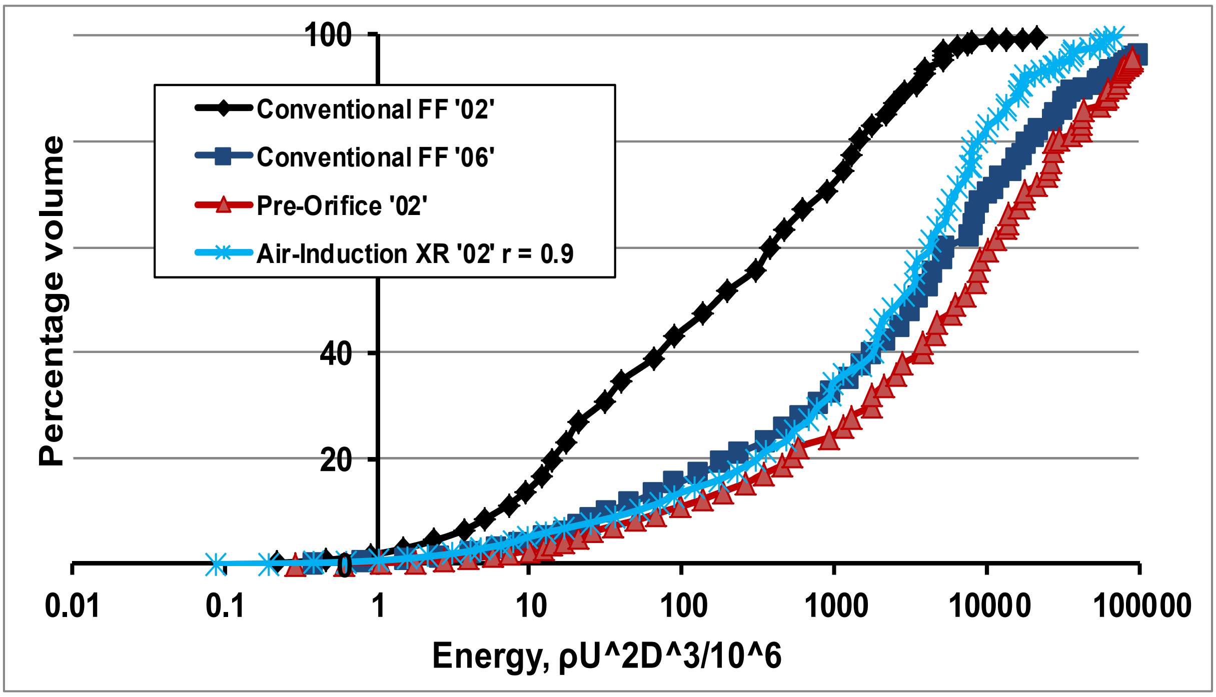


Figure 27. Measured percentage of spray volume/impact energy correlations for four of the nozzles used in the study.

The use of the Retention Parameter (Figure 26) does enable discrimination between all of the nozzle types, although comparison with the measured deposits indicates that the relative magnitudes for the air-induction and pre-orifice nozzles are not in the same order for the two measures. Generally, higher values of the retention parameter correspond with lower measured deposits. It should be noted that most of the relationships plotted in Figures 25 – 27 take no account of the presence of air within the droplets and the calculations of parameters such as impact energy assume that all the droplets contained only the spray liquid water. In Figure 26, the calculations have been made for droplets assuming a relative density (r) of either 1.0 or 0.9. Using a relative density figure of 0.9 reduces the retention parameter as expected, indicating that higher deposits would be measured such that deposition would then match or exceed that with the smaller conventional nozzle. This was not observed in the deposit experiments – see Figures 13, 14 and 15. Taking account of droplet velocity would also cause complications if nozzles were angled in the forward/backward direction on a boom. The velocities plotted in Figures 25 – 27 relate to the vertical components of velocities and these would be reduced if nozzles were angled and changed if nozzles with different spray fan angles were used. It was therefore concluded that the potential for nozzle classification in respect of deposition and efficacy could potentially be addressed if aspects of droplet velocity were included in any analysis. Further work is required to consider the anomalies identified in this study, but measurement of the physical characteristics of the spray (droplet size, velocity and volume distribution patterns) to define a deposit parameter in an extended classification scheme would be advantageous. This further work would also need to:

- Evaluate the repeatability of droplet velocity measurements;
- Consider the effects of changes to spray angle at the nozzle.

This study has investigated the use of target deposition as an indicator of likely product efficacy when using a given nozzle/spray quality. While it is likely that for many products used to treat arable crops the magnitude of target deposits will be a major factor influencing efficacy, for some, parameters such as surface coverage and the form of the spray deposit may also be important. Given this, and the lack of consistent and repeatable deposit data that could be linked to a definition of spray quality, it has been concluded that measurements of deposit distributions are unlikely to form a basis for spray quality classification in terms of likely efficacy.

6.2. Relating to the definition of a drift risk indicator within an extended spray classification scheme

Results from the wind tunnel assessment of spray drift gave relative values that were in line with expectations. Using conventional flat fan “02” and “015” nozzles at pressures of 4.0 and 3.0 bar, respectively, gave relative drift magnitudes that were some 65 and 146% greater than those from the reference “03” nozzle. Currently in the UK the only performance measures that relate to spray drift from agricultural applications are within the LERAP scheme. Four drift categories are defined in relation to a reference condition that uses an “03” nozzle (FF110/1.2/3.0) operating on a conventional boom at a height of 0.5 m above the top of a crop or the ground as follows:

- No rating – drift of greater than 75% of that from the reference condition

- A one star rating – drift greater than 50% and up to 75% of that from the reference condition
- A two star rating – drift greater than 25% and up to 50% of that from the reference condition
- A three star rating – drift up to 25% of that from the reference condition.

All spray drift classifications to date therefore relate to the ability of application systems to reduce drift in comparison with this defined reference condition with no means of giving users information about systems with a higher risk of drift. Results from the wind tunnel studies suggest that for drift ratings relevant to boom sprayers operating over arable crops a symmetrical scheme could be envisaged based on the same reference condition as follows:

- A minus one star rating – drift greater than 125% of the reference condition
- A minus two star rating – drift greater than 150% of the reference condition
- A minus three star rating – drift greater than 175% of the reference condition.

This would give relatively good resolution of systems that were likely to give an increased drift risk so that, for example, the flat fan "02" at 4.0 bar pressure would be classified as a 'minus two star rating' whereas the "015" nozzle at 3.0 bar pressure would be a 'minus three star' rated nozzle. Some care would be needed to define the terminology that could be used in any such system – the minus star ratings have been used here only as examples. Previous work looking to define drift risks that could be greater than those of a reference system had considerable difficulties with such terminologies recognising that terms such as 'high drift' could give difficulties for the image of the industry (Southcombe et al., 1997). Application systems giving higher drift levels than a conventional boom fitted with "015" nozzles operating at 3.0 bar would be classified as 'minus three star' and this is appropriate for systems operating over arable crops – it may be less appropriate for air blast sprayers operating in bush and tree crops and for some specialised applications to vegetable crops. Deriving the 'minus ratings' could use the same wind tunnel protocols as for data generation in support of claims for LERAP star ratings. These protocols are currently under review but any changes are unlikely to change the ability to assess levels of drift risk above those of the reference.

It is particularly noticeable that the results from the field experiments with the 'high drift' systems did not give levels of downwind deposits on either ground collectors or airborne sampling lines that were as high as expected. This almost certainly reflects a greater level of dispersion from the more driftable spray such that it is travelling to greater distances downwind before depositing and is creating an airborne plume, components of which are above the height of the collectors used in the study (to two metres). This result has important implications when defining standard protocols that might be used for determining high spray drift ratings. The current LERAP test protocols make provision for conducting experiments either in a wind tunnel or under field conditions. Results from this study suggest that making assessment of drift risk under field conditions when systems are likely to give high drift values can be difficult and involve the sampling of large airborne plumes and/or assessments of ground deposits over relatively large distances.

6.3. Concept relating to a revised spray/nozzle classification scheme

The aim of the project was to have a revised classification system that would encompass all types of spray delivery system such that product label statements such as “Apply as a medium quality spray in 200 litres of water” could be complied with using a wide range of application systems. The original project proposal also indicated that a revised classification scheme would have two components: one relating to the likely efficacy of a spray and a second relating directly to drift risk. This concept had previously been proposed by Southcombe *et al*., (1997) and used in the AHDB Cereals & Oilseeds Nozzle Selection Guide (2010). This approach has been further developed during the project and is considered to be an appropriate basis for nozzle selection when operating boom sprayers over arable crops.

The original project proposal recognised that sprays that had very different characteristics from those of the reference nozzles, either because of air-inclusions in the droplets or a different size/volume distribution, could have a different performance in terms of likely efficacy – see Figure 28.

The project consortium identified that providing the likely efficacy component in a revised scheme could remove the need to define test criteria and separate classification matrices for sprays with air-included droplets and size/volume curves that were very different from those of reference nozzles. However, given that the results of this project have indicated that deriving this efficacy component from measurements of deposits is not likely to be robust, then alternative approaches will again need to be considered.

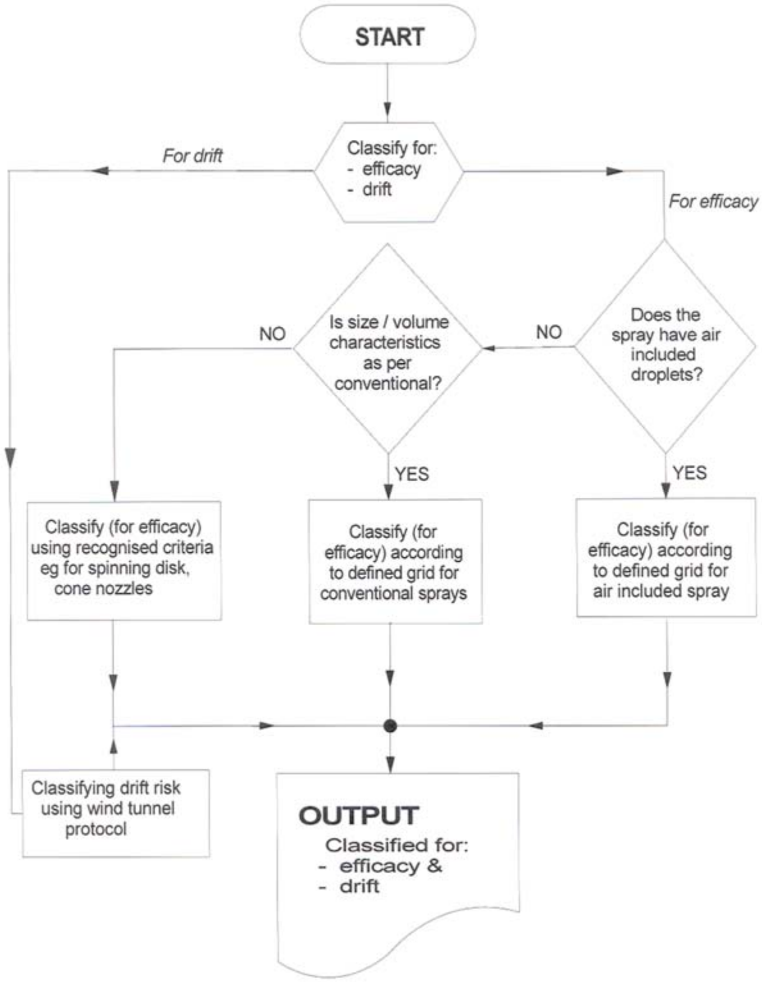


Figure 28. Flow diagram for a proposed spray classification system as outlined in the original project proposal.

Classifying air-induction nozzles using protocols based solely on droplet size distributions would mean that they cannot be used in compliance with label statements such as in the above example because the sprays would be classified as coarse, very coarse or extra coarse. However, there is now a substantial body of evidence that shows that the use of such nozzles would give acceptable efficacy with a wide range of products used to treat arable crops and deliver advantages in terms of improved drift control. One possible approach to addressing the issue of classifying sprays from air-induction nozzles that has been proposed involves determining the quantity of air included in droplets and then calculating an effective droplet size without air that can be related to reference nozzles within the existing system. This assumes that this quantity of air can be measured (Faggion *et al.*, 2006) and that the percentage of air included is constant over the droplet size range or could be determined. Results from this work confirm that such an approach does not provide an effective way of accounting for the effect of air in droplets on spray deposition characteristics and therefore is not an appropriate way of effectively classifying air-induction nozzles.

Given that results of this study have shown that spray classification on the basis of a measured deposit magnitude/distribution is unlikely to be practically feasible and that approaches involving including droplet velocity and trajectory have not led to an inclusive classification scheme, it is now considered that it is likely that the practical future option is to treat air-induction nozzles as a separate category of spray generating device. This is the approach taken in the AHDB Cereals & Oliseeds Nozzle Selection Chart (2010) and could in future be incorporated into product label statements – e.g. “Apply as a medium quality spray or using a small droplet air-induction nozzle with the product in 200 litres of water”. Further work is required to:

- Improve the definition of “small droplet” and “large droplet” air-induction nozzles – the current approach uses a relative measure of droplet size with no defined boundaries and no criteria for what constitutes an air-induction nozzle (should twin-fluid nozzles be included?; should the specification relate to air-included sprays?): work is needed to ensure that this approach is robust and to consider defining boundary conditions;
- To update the measurement protocols and reference nozzle specifications within the existing BCPC classification scheme: discussions have taken place regarding the definition of an International Standard for agricultural spray nozzle classification and there is a need to ensure that approaches used within the UK are consistent with those used in other parts of Europe and particularly in the Central Zone as well as other parts of the world;
- To review the approaches to the classification of spray generation systems that have droplet size/volume distributions that are very different from those of the reference flat fan nozzles once revised protocols and reference conditions have been produced.

7. CONCLUSIONS

It was concluded that:

a) A spray classification scheme that has separate components relating to both likely product efficacy and drift is feasible and would provide users with additional useful guidance relating to nozzle selection particularly for boom sprayers operating to treat arable crops.
b) A component of a spray classification scheme based on measurements of spray deposits on a defined target matrix (either deposit distributions or magnitudes) is unlikely to be sufficiently repeatable and robust to provide a consistent indicator of product efficacy.
c) A component of a spray classification relating directly to the expected drift risk from systems operating in conjunction with boom sprayers could be obtained from wind tunnel experiments conducted to protocols similar to those used to generate data to support claims for star ratings within the existing LERAP scheme.
d) While the project was not able to deliver a complete specification for a revised spray/nozzle classification scheme, results having important implications for improving the operation and evaluation of boom sprayers operating over arable crops were delivered:

(i) A specification for a test liquid for use in nozzle testing and spray application experiments that did not use a nonyl-phenol surfactant;

(ii) Data that supported the approach taken in the latest version of the AHDB Cereals & Oilseeds Nozzle guide in which separate indications of performance were given for likely product efficacy and drift risk and in which air-induction nozzles are considered as being either “small droplet” or “large droplet” designs;

(iii) Measurements of spray deposits on a range of target geometries that confirmed that deposits when using air-induction nozzles were substantially greater than those expected from extrapolations of droplet size/deposit data obtained for conventional flat fan nozzles;

(iv) Evidence that factors other than droplet size (particularly droplet velocity) are important in determining deposit on targets and could therefore be the basis for future work in developing classification systems;

(v) Results that showed that application volumes in the range 75 to 100 L/ha gave higher deposits on small (<3.0 mm) targets that were greater than when using higher application volumes particularly when the targets were mainly vertical;

(vi) Results that showed that the deposits on small vertical targets was increased by more than a factor of two when the wind speed in the region of the target was increased within the range of acceptable conditions for field applications: these wind speed conditions at target height were related to the range of recommended wind speed measured at boom height;

(vii) Measurements of the droplet size and velocity distributions within the sprays were used to calculate a Retention Parameter that discriminated the sprays from the applications systems used in the study but did not directly correlate with measured deposits: results from this part of the work indicated that it may be possible to define a deposition parameter that could be used in a revised classification scheme but that further work is required to examine the linkage with measured deposits, investigate measurement reliability and account for nozzle parameters including spray angle.

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