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Techniques for measurement of droplet size and velocity distributions in agricultural sprays

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Two techniques for measuring the size and velocity of droplets in agricultural sprays produced by hydraulic flat fan nozzles have been evaluated for their ability to produce consistent results. These were a one-dimensional phase Doppler particle analyser (PDA) and a two-dimensional imaging probe of a Particle Measuring Systems (PMS) instrument, both measuring velocities in a single plane and operated in conjunction with a computer-controlled nozzle transporter to enable the whole spray to be sampled.

The different operating principles of the instruments resulted in different droplet size and velocity distributions in relatively dense, polydispersed sprays. PDA gave consistently lower values for the volume median diameter and higher droplet velocities than PMS. PMS gave lower percentages of spray volume in droplets less than 100 μm in diameter, while the PDA indicated some large droplets that were not detected by PMS. The required sample size was smaller for PMS (3000 droplets) than for PDA (13,000 droplets).

Both instruments are useful for measuring the characteristics of agricultural sprays, providing that their limitations are recognized. Appropriately configured, such systems enable droplet size and velocity distributions, entrained air velocities, droplet trajectories and the spatial structure of sprays to be determined. © 1997 Elsevier Science Ltd

Keywords: droplet size; droplet velocity; nozzle performance

Agricultural pressure nozzles produce sprays with a distribution of droplet sizes and velocities (Lefebvre, 1993). It is important to quantify and control these distributions because they influence droplet trajectories and interactions with the target. The efficacy of a particular pesticide is often dependent upon droplet size (Hislop, 1987). Good, uniform coverage of the target is usually best achieved with small droplets. Larger droplets retain their momentum for longer and are therefore less prone to interact with cross winds which can cause spray drift. Models of droplet trajectories have been developed (e.g. Thompson and Ley, 1983; Picot *et al.*, 1986; Walklate, 1987; Miller and Hadfield, 1989; Smith and Miller, 1994) to predict likely spray drift. These require information about droplet size distributions, initial velocities and also the velocity of the air entrained within the spray fan.

Another important reason for measuring droplet size distributions is to assess the performance of a particular nozzle. Nozzle classification methods have been devised which use droplet size distributions from reference nozzles as standards to define spray quality categories (Doble *et al.*, 1985). Droplet size distributions of test nozzles can be compared to those of standard nozzles, allowing the relative quality of the test spray to be determined.

Methods of measuring droplet size distributions in agricultural sprays have been reviewed by Parkin (1993). There are three common methods employing laser technology to measure droplets in flight. Laser-based instruments are relatively non-intrusive and can sample large numbers of droplets efficiently. However, the different techniques can result in different measured distributions, particularly in dense polydisperse sprays commonly used for pesticide application.

The theories behind the different laser measurement techniques were reviewed by Lefebvre (1989). Diffraction of laser light by droplets in a spray cloud, employed in instruments such as the Malvern particle sizer, can be used to determine a spatially-averaged droplet size distribution. Droplet velocities are not measured with this technique. Droplet imaging allows size and velocity to be determined of individual droplets passing through a small sample volume. This is used, for example, by the Particle Measuring Systems (PMS) imaging probe (type OAP-2D-GA1). A more recently developed technique, phase Doppler analysis, is an extension of laser Doppler anemometry which measures particle velocity. One-dimensional phase Doppler analysis (PDA) uses three detectors to calculate droplet diameter from the phase difference in scattered light between pairs of detectors. Both droplet imaging and PDA measure temporally-averaged samples of spray, i.e. the droplets passing through a small sample volume in a given period of time (Simmons, 1984). Consequently, the results obtained by these techniques are not directly comparable with those produced by spatial sampling such as the Malvern particle sizer. It is possible to convert temporal samples to spatial samples when velocities are known to allow comparison between instruments (Arnold, 1987). The possibility of converting spatial samples to temporal samples has also been investigated (Chapple *et al.*, 1995).

The use of the PMS for measuring agricultural sprays is well established and some of the procedures for its use have been investigated (Lake and Dix, 1985). Arnold (1987) compared results from the Malvern and the PMS instruments and Young and Bachalo (1988) investigated the differences in measurements of droplet size between all three laser techniques and found that comparative data can be obtained when measuring reference materials. However, they found that agreement between instruments deteriorates for coarse agricultural sprays. Comparisons of velocity measurements were not made.

Measurements of droplet size and velocity with PMS and PDA instruments are compared in this paper and some of the reasons for the differences between them will be discussed. Possible methods for minimising these differences are investigated. Because the size distribution of droplets in agricultural sprays is not homogeneous but depends on the position within the spray (Butler Ellis *et al.*, 1997; Chapple and Hall, 1993), it is important to ensure that the strategy which is chosen for quantifying a spray provides a representative sample of droplets, both in terms of numbers of droplets detected and the position at which they are measured. Different sampling strategies are evaluated and the method which was found to give the most reliable measurement of droplet size distribution for a flat fan nozzle is described. Methods of analysing the droplet size and velocity data from PDA and PMS for assessing the spray produced by agricultural flat fan nozzles are also outlined.

Equipment

Particle imaging

An OAP-2D-GA1 optical array imaging probe (Particle Measuring Systems, Boulder, CO, USA) was used, connected to a PMS-1057A module (which has been upgraded to PMS-1057C standard) installed in an IBM compatible PC and run through PMS OAP Data Acquisition and Control System 100G software. The probe was configured to measure droplets between approximately 14 and 1250 μm in nominal 20 μm bins.

The total length of the laser beam through which the falling droplets can be measured has a maximum value of 61 mm. Small spacer tubes are used to shield the optics from spray splash and reduce the length of the beam. This reduces the number of droplets in the sample volume at any one instant. The effect of the length of the sampling beam on measurement performance of the PMS was investigated by measuring droplet size and velocity distributions from a range of nozzles. The length of sampling beam was varied by using different length spacer tubes. The variations in VMD and small droplet velocities with length of sampling beam are shown in *Figures 1* and *2*, respectively. A practical limitation to reducing the beam length is the impaction and shedding of small droplets from the spacer tubes into the sampling beam. Observations made during measurements indicated that this was clearly visible at a beam length of 10 mm and may also be significant at greater beam lengths.

In dense spray clouds the 'probe busy' time, which indicates probe activity and is related to the rate at which droplets pass through the sampling beam, can exceed the recommended range of 5 to 10% (Particle Measuring Systems, 1988). Reducing the sample volume by reducing the length of the sampling beam can help to alleviate this problem. For the data shown in *Figure 1* with an F110/0.4/3.0 nozzle, the probe busy time varied between 14% for a beam length of 9 mm to 32% for a beam length of 59 mm. This suggests that the probe activity may still be too high and there may be some associated loss of accuracy. Subsequent measurements were made with a beam length of 43 mm, as a compromise between minimising probe activity and causing impaction and

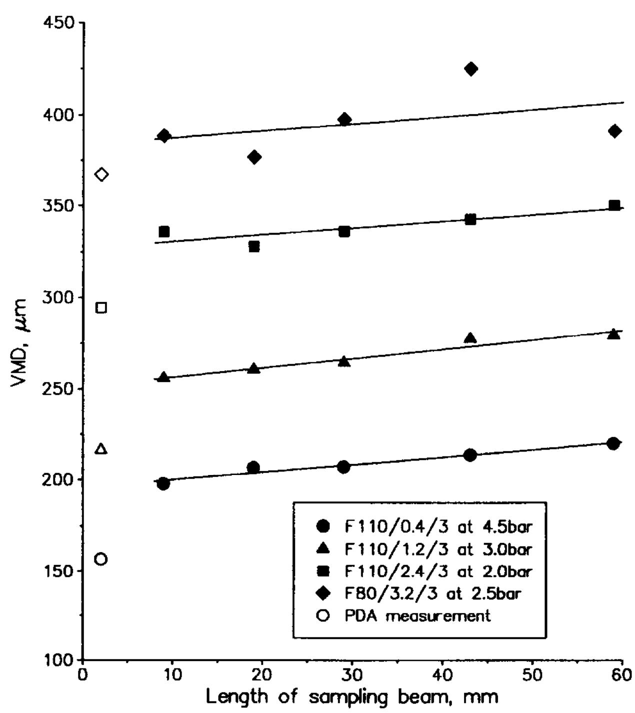

Figure 1. The effect of length of sampling beam on measurements of VMD made with the PMS and compared with a single PDA measurement. Measurements are made with four nozzles spraying water plus 0.1% non-ionic surfactant, 350 mm below the nozzle, using a full scan

shedding of small droplets from the spacer tubes into the sample volume.

Phase Doppler analysis

A Dantec Particle Dynamics Analyzer System (Dantec Ltd, Bristol, UK), comprising an argon-ion 400 mW laser with fibre optic cable link to 55X series transmitting optics, 57X10 receiving optics connected to a 58N10 PDA signal processor and PC running the SIZEware™ software was used for this work. The instrument was operated using near-forward scatter (first order refraction) with the receiving optics set at an angle of 70° to the incident beam and arranged to measure the vertical component of droplet velocity.

Measurement ranges for both diameter and velocity can be varied through changes in the optical and electronic configurations. Laser wavelength, laser beam separation, angle adjustment of the receiving optics, lens focal length for both transmitting and receiving optics and signal processor bandwidth have the most significant effect on measurement ranges (*Figure 3*). Under normal operating conditions, when measured at a typical height of 350 mm, most agricultural hydraulic nozzles can be expected to produce droplets within the range 0–900 μm and with velocities up to approximately 20 m s^{-1}. The argon-ion laser has maximum intensity at a wavelength of 514.5 nm. To obtain the necessary size and velocity ranges, transmitting and receiving lenses with a focal length of 600 mm, a beam separation of 13 mm, angle adjustment of 2 and bandwidth of 1.2 MHz were selected. These settings give a diameter range of 0–875 μm and velocity range of −7.1 to 21.4 m s^{-1} and are therefore suitable for most measurement situations involving agricultural spray nozzles.

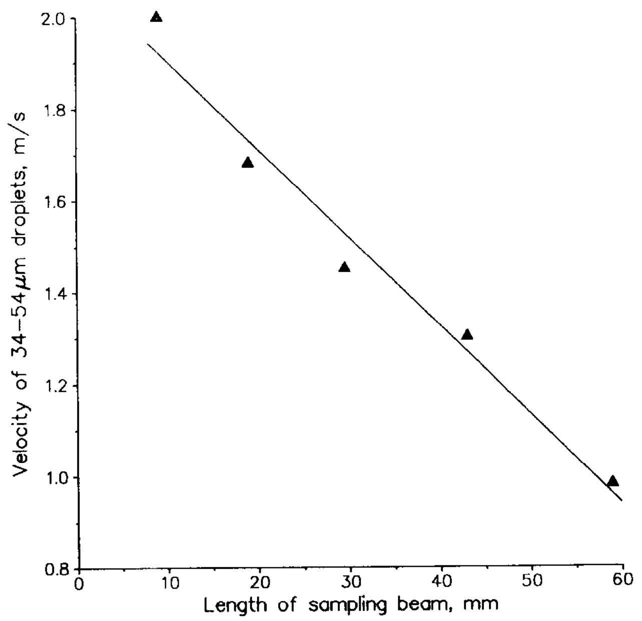

Figure 2. The effect of length of PMS sampling beam on the measured mean velocity of droplets in the range 34–54 μm from an F110/1.2/3.0 nozzle spraying water plus 0.1% non-ionic surfactant at 3 bar pressure 350 mm below the nozzle

Transporter

An X–Y transporter (Time and Precision Ltd, Basingstoke, UK) enabled spray nozzles to be moved to any position within a 1100 mm square frame to an accuracy of 0.1 mm at speeds between 1 and 50 mm s^{-1}. Using PC-based software, the transporter can be programmed to move to any position, or in a variety of patterns to effectively sample a complete cross-section of nozzle output (*Figure 4*).

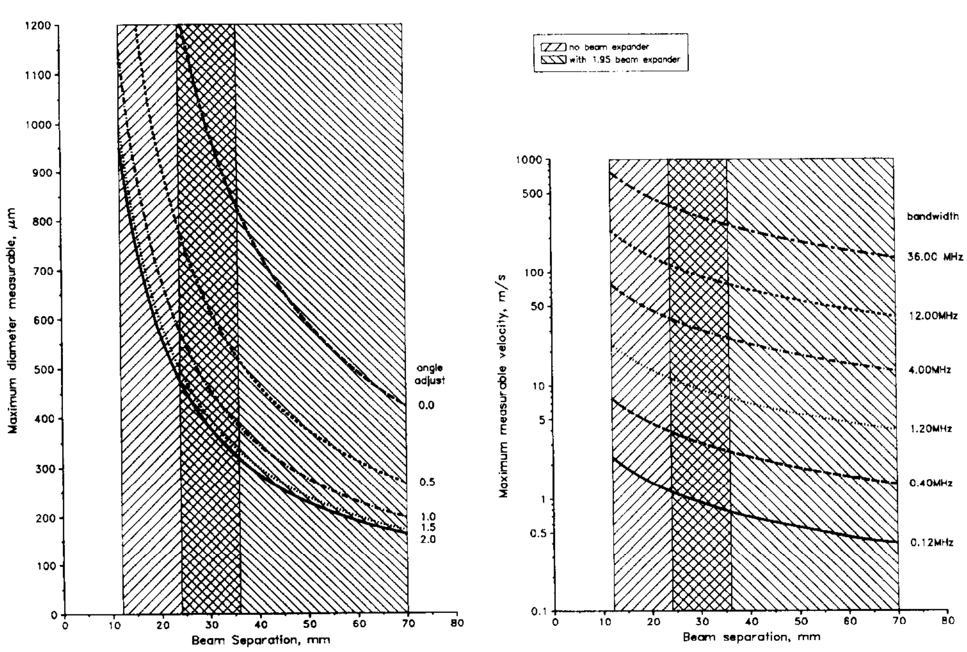

Figure 3. The effect of beam separation, angle adjustment and bandwith on diameter and velocity ranges with Dantec PDA. Data obtained from Dantec Sizeware software

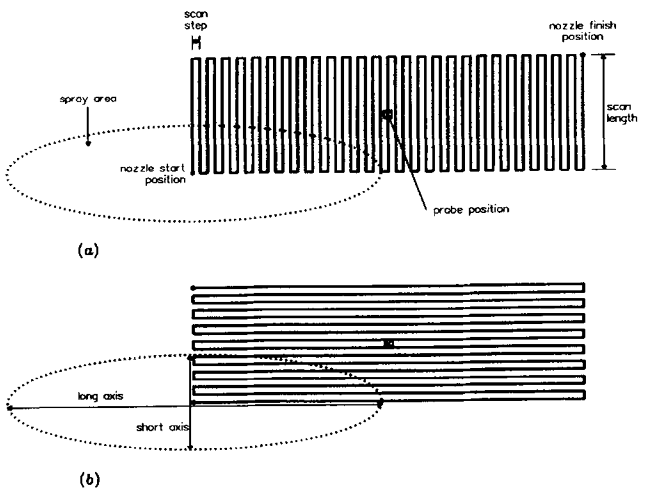

Figure 4. Transporter scan patterns for characterizing flat fan nozzles: (a) scanning parallel to short axis; (b) scanning parallel to long axis

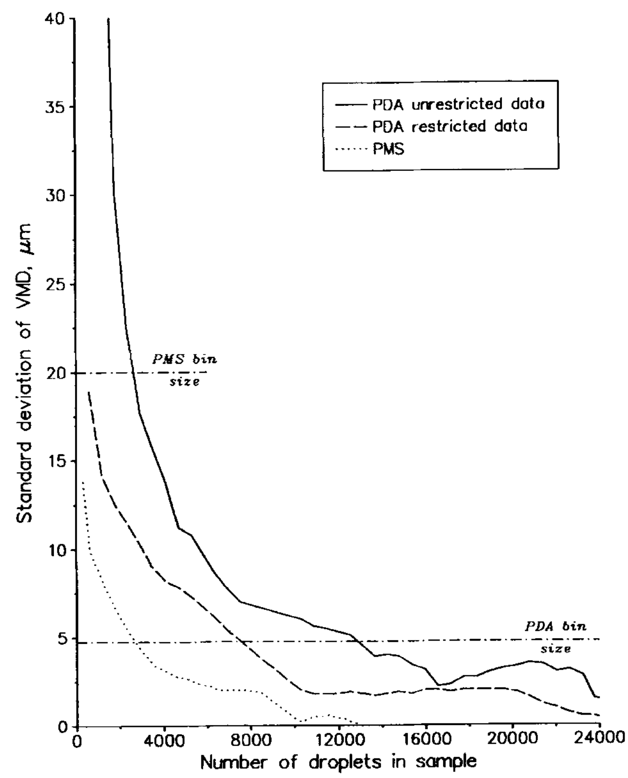

Figure 5. Variation of standard deviation of VMD with the number of droplets in the sample for an F110/0.8/3.0 nozzle operated at 3.5 bar spraying water and 0.1% non-ionic surfactant

Sampling techniques

Both PMS and PDA instruments have small sampling volumes. The actual sampling volume varies with depth of field and droplet diameter for the PMS and beam separation and droplet diameter for the PDA. Positioning the sample volume at a single location provides detailed information about that location. In order to increase the volume over which droplets are sampled, the sample volume has to be moved relative to the spray. For the system used in this study, the sampling volume was stationary and the nozzle was moved by the transporter in either horizontal direction. The vertical position was constant, usually at 350 mm below the nozzle, representing the approximate height of the nozzles above the crop for 110° nozzles at 0.5 m spacing.

Number of droplets

It is necessary to collect sufficient droplets from the spray to ensure that a representative sample is taken. Parkin (1993) suggested that satisfactory results were unlikely to be obtained with a PMS with samples containing less than 2000 droplets; Adams *et al.* (1990) recommended 10,000 droplets with a PDA. However, the number of droplets required for an adequate sample depends upon the type of nozzle — a spinning disc which produces a narrow range of droplet sizes may require fewer droplets for adequate sampling than a flat fan nozzle with a wide range of droplet sizes.

Measurements were made using both PMS and PDA instruments to determine VMD of the droplets at the centre of the spray produced by an F110/0.8/3.0 medium spray quality flat fan nozzle (Lurmark F11002) at 3.0 bar pressure. A total of 24,000 droplets was measured and different portions of the data were analysed to evaluate how the standard deviation of the VMD varied with number of droplets in a sample. The criterion for determining the minimum number of droplets required was to achieve a standard deviation equal to the bin width of the measuring instrument. *Figure 5* shows that for the PDA (solid line) approximately 12,000–14,000 droplets are needed to achieve this. Increasing the number of droplets beyond this value gains little in reducing the variation in VMD. (The dashed line in *Figure 5* refers to a technique where some of the data is excluded, which will be discussed later.) The PMS (dotted line) requires few droplets (<1000) to achieve a standard deviation in VMD less than its 20 μm bin width. Increasing the number of droplets to between 2000 and 4000 reduces the standard deviation to the same level as the PDA bin width. Similar results were obtained for fine and coarse flat fan nozzles.

Scanning patterns

Neither a single position nor a one-dimensional scan is necessarily representative of the whole spray from a flat fan nozzle, as can be seen in *Figures 6* and *7*, where the variation of VMD in the two horizontal directions for F110/1.6/3.0 and F110/0.6/3.0 nozzles, measured with the PDA, is shown. Consequently, if information about the whole spray is required, scanning the whole spray cross-section is necessary.

When measurements of the whole spray or over a large region of the spray are required, a scanning pattern has to be devised to ensure that the region is sampled adequately, either by scanning parallel to the short axis of a flat fan (*Figure 4*a) or by scanning parallel to the long axis (*Figure 4*b). Chapple and Hall (1993) demonstrated that there was some variation in VMD with position for a Teejet XR8003VS nozzle, but concluded that a single scan along the long axis gave an adequate representation of the whole spray.

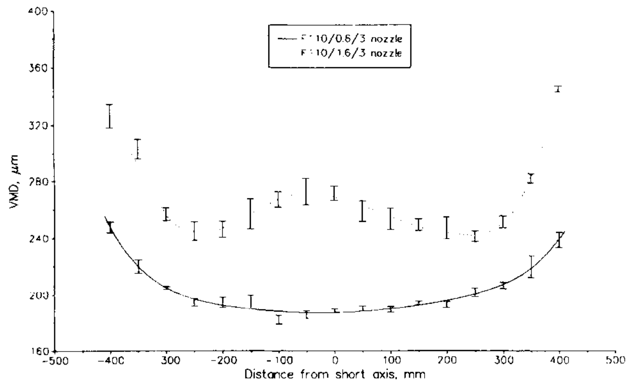

Figure 6. Variation of VMD with distance from the short axis for two nozzles spraying water only at 3 bar, measured 350 mm below the nozzle with the PDA, scanning parallel to the short axis

This may be true for some nozzles but is not necessarily the case. Butler Ellis *et al.* (1997) have shown that changing the spray liquid can alter the distribution of droplet sizes along the long axis and also change the thickness of the spray which may alter the distribution of droplet sizes along the short axis. A single long axis scan may not therefore be representative of the whole spray in all circumstances.

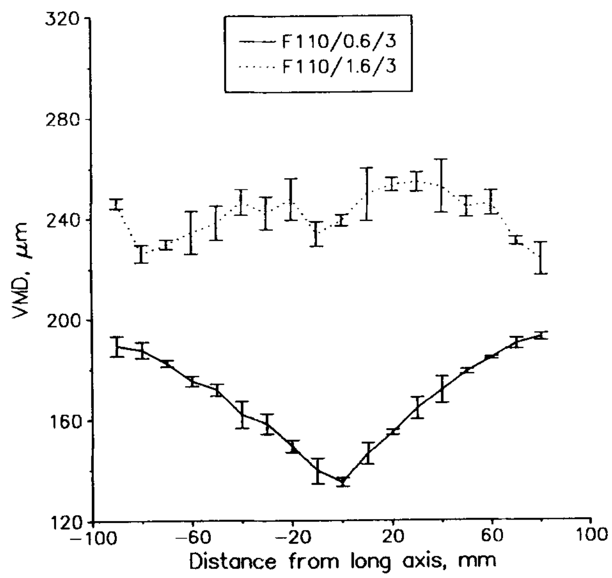

Figure 7. Variation of VMD with distance from the long axis for two nozzles spraying water only at 3 bar, measured 350 mm below the nozzle with the PDA

Although the total length of travel is the same for similar area and scan steps, scanning parallel to the long axis was slightly quicker because there were fewer time-consuming direction reversals. However, a full scan parallel to the short axis of the fan was shown to give less variable results, as shown in *Table 1*, and is therefore our preferred method for flat fan nozzles. The variability in scanning along the long axis could probably be reduced by reducing the scan step. The minimum number of scans required to adequately sample the full spray will depend on the variation of spray characteristics along the axis which is in turn dependent on nozzle design, operating pressure and liquid properties. In practice the rate at which the droplet size distribution changes with horizontal position will dictate the step length and the speed of the transporter will determine the duration of the measurement and the number of droplets detected. Measurements of the effect of scan speed showed no differences between 1 and 50 mm s^{-1} and therefore, within these limits, the scan speed can be adjusted to minimise the experiment duration, providing an adequate number of droplets are measured.

Although a full scan enables all parts of the spray to be sampled, there is still an implicit assumption that all parts of the spray are sampled in the same way. This may not be the case since the spray fluxes are higher in the centre of the spray and therefore the PMS, for example, may sample less efficiently in the centre of the spray than at the edges.

Nozzle height

Lake and Dix (1985) found that there was very little effect of nozzle height above the measurement volume on VMD when measured with the PMS. Young (1990) showed that the VMD directly below the nozzle decreases with height when measured with a PMS. This is to be expected because the spray density declines as the height increases, allowing the PMS to take a more representative sample.

Measurements made with PDA scanning along the short axis (*Figure 8*) show that there is a significant increase in VMD with height. It was originally thought that the reason for this might be that the droplet velocities decline with distance below the nozzle, making the droplet velocities increasingly small compared to the range of velocities measurable

Table 1. Effect of scan pattern on variation in VMD. Scan step 20 mm, scan speed 40 mm s^{-1}, F110/1.6/3.0 nozzle spraying 0.1% solution of non-ionic surfactant at 2.5 bar pressure. Measurements made with PDA

	Scanning parallel to short axis		Scanning parallel to long axis	
Replicate No.	No. of droplets	VMD (μm)	No. of droplets	VMD (μm)
1	10,805	265.0	12,199	258.1
2	11,249	268.6	11,725	266.2
3	10,900	268.9	11,386	263.6
4	11,780	265.6	11,168	266.8
5	12,014	264.7	11,674	262.1
6	11,731	267.6	10,453	277.2
mean	11,413	266.7	11,434	265.7
standard deviation	501	1.9	594	6.5

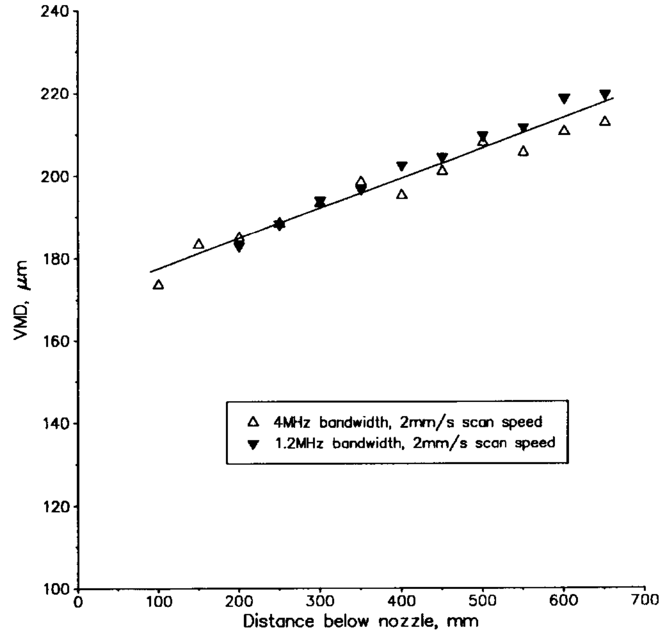

Figure 8. Variation of VMD with distance below an F110/0.6/3.0 nozzle, measurements made with the PDA scanning along the short axis

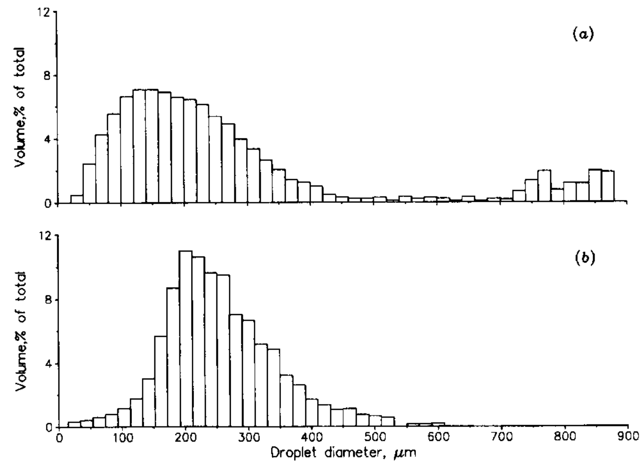

Figure 9. Comparison of volume distributions with (a) PDA, range 0–875 μm, and (b) PMS, range 0–1250 μm from an F110/0.8/3 nozzle spraying water and 0.1% non-ionic surfactant at 3.5 bar. Measurements were made 350 mm below the nozzle and scanned along the short axis

by the PDA, leading to a biased sample. However, reducing the velocity range by reducing the bandwidth of the instrument showed little change in VMD, so it is unlikely that this is the cause. Chapple and Hall (1993) showed that an Aerometrics PDA underestimated considerably the volume flux in the centre of the spray, suggesting that it is possible that the PDA samples less efficiently at high densities. However, it will be shown later that flux measurements with the Dantec PDA did not demonstrate this effect.

Since there is no apparent reason why the PDA should be influenced by droplet density or droplet velocities, it is likely that VMD does increase with nozzle height. Therefore, it is important when making comparisons between sprays that, whichever instrument is used, they are always measured at the same height to ensure consistency.

Comparison between PMS and PDA measurements

Examples of the droplet size distributions made with both PMS and PDA instruments are shown in *Figure 9*. The PDA data was converted to the same bin width as the PMS using custom-written software at Silsoe Research Institute. It can be seen that the PDA measured smaller droplets (<200 μm) and measured large droplets which the PMS did not see. Even though there are often no more than two or three of these large droplets, they can have a significant effect upon the volume distribution.

The PMS sees fewer small droplets than the PDA in a dense polydisperse spray because firstly they may be completely obscured by larger droplets and secondly the probability of two small droplets appearing simultaneously within the sample volume is high. (The PMS rejects images where there are two or more droplets present). The same is true of the PDA, but the sample volume is considerably smaller which reduces the probability of two droplets appearing together. Consequently, the PMS generally gives a higher VMD than the PDA for flat fan nozzles. For the distributions shown in *Figure 9*, the VMD with the PMS was 244 μm and that with the PDA was 210 μm. In lower density sprays and sprays with a narrow range of droplet sizes, the PMS and PDA measurements are closer. For example, measurements of a spray produced by a spinning disc gave VMDs of 140 μm for the PMS and 146 μm for the PDA.

Many of the large droplets measured by the PDA which are not seen by the PMS are thought to be caused by a few erroneously interpreted signals and not by genuine droplets. This is caused by the 'trajectory effect' (Bachalo, 1994) and the 'slit effect' (Durst *et al.*, 1994) and is a system-inherent error that cannot be avoided in conventional one-dimensional PDA systems. The consequence of these effects is that droplets larger than the diameter of the sample volume (approximately 300 μm for our settings), if they follow a certain trajectory, can reflect light into the receiving optics, rather than refract light, leading to an erroneous calculation of diameter. These effects can be compensated for by additional hardware and software (DualPDA, Dantec Ltd, Bristol, UK) which has recently become available (Tropea *et al.*, 1995). Droplet size distributions in polydisperse sprays can appear to be significantly changed by using the DualPDA, although there are no data available with this new system relating to agricultural sprays.

In the 1-D system which was used in the work described in this paper, some of the erroneous droplets were eliminated during data analysis. The PMS was used to determine the size of the largest droplets present and droplets greater than this were excluded from PDA data. Erroneous droplets occurring within the range of drop sizes produced by the nozzle cannot be eliminated, however, and it is also possible that some of the eliminated droplets were genuine. Because these effects occur with all polydisperse sprays, measurements of spray quality can be made relative to reference nozzles, such as in the BCPC classification scheme (Doble *et al.*, 1985), without excluding the erroneous droplets. However, since a small number of the large droplets can significantly affect the volume distribution, it is useful for more detailed investigations to eliminate them from the analysis.

The variation of VMD with number of droplets can be considerably reduced when the largest erroneous droplets are excluded from the analysis. Repeating the calculation of the variation of standard deviation in VMD with droplet numbers, but with droplets larger than the largest recorded by the PMS excluded, shows that a significant reduction in the number of droplets needed to provide an adequate sample can be obtained (*Figure 5*, dashed line). This suggests that the number of droplets required for a standard deviation equal to the PDA bin width is approximately 8000. Again, a similar result was obtained for fine and coarse flat fan nozzles.

Typical droplet velocities measured by the two instruments are shown in *Figure 10*. Vertically below the nozzle, the PMS gives significantly lower values than the PDA. The reason for the differences is not clear, since when measuring a spray with a narrow range of droplet sizes and velocities, such as that produced by a spinning disc, the two instruments gave similar velocities (*Figure 11*). The results in *Figure 2* showed that reducing the length of the sampling beam on the PMS increased the measured velocity of droplets between 34 and 54 μm from a flat fan nozzle. This suggests that differences between the two instruments are caused by a sampling bias which occurs in dense polydisperse sprays when the PMS underestimates small droplet velocities.

Additional measurements

Evaluation of droplet trajectories

Droplet trajectories can be evaluated by measuring horizontal and vertical components of velocity. The PDA was rotated on its optical bench through 90° so that horizontal components of velocity could be measured. This was carried out at a position 350 mm below the nozzle and 350 mm from the centre line. If

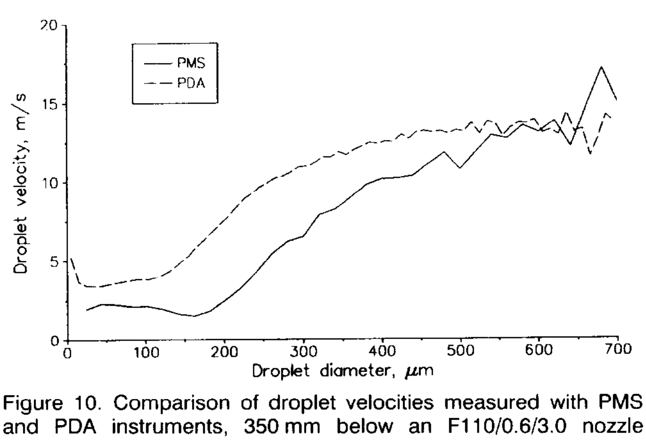

Figure 10. Comparison of droplet velocities measured with PMS and PDA instruments, 350 mm below an F110/0.6/3.0 nozzle spraying water at 3 bar, scanning along the short axis vertically below the nozzle

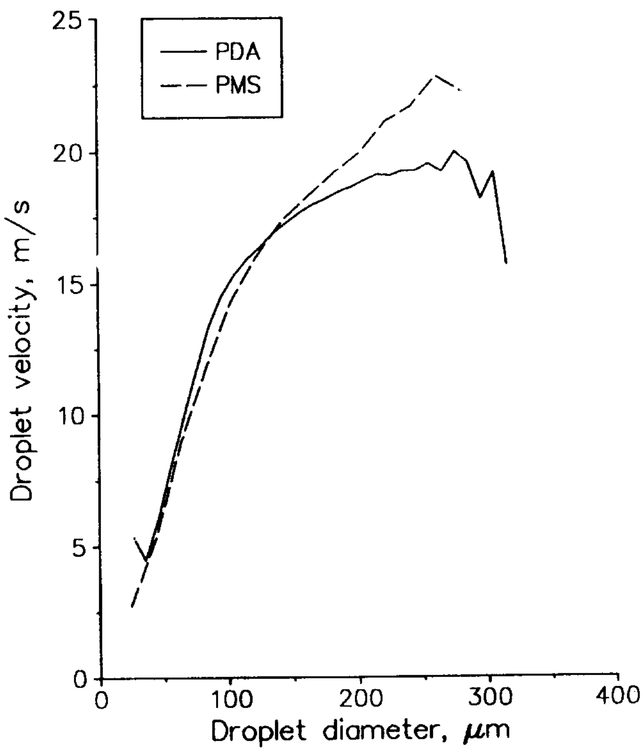

Figure 11. Comparison of droplet velocities measured with PMS and PDA instruments 40 mm from a spinning disc rotating at 3720 rpm and spraying 0.175 L min^{-1}

all droplets continued along their initial path, then at this position they would be travelling at 45° to the vertical, giving identical horizontal and vertical components of velocity. However, it is possible that both gravity and entrained air influence droplet trajectories causing deviations from their original path. *Figure 12* shows the calculated angle of trajectory for each droplet size class. It can be seen that, for droplets below about 250 μm, the deviation from a 45° trajectory increased as the droplet size decreased, which is probably the result of interactions with the entrained air. Gravity would be expected to affect the largest droplets most, whilst entrained air would have the greatest influence on the smallest droplets. At positions further from the nozzle, it may be possible to see deviations from the initial 45° trajectory by the larger droplets, where the effect of gravity may become more important than that of entrained air.

Determination of footprints and fan angles

The PDA was used to determine the width of the spray from a flat fan nozzle by considering droplet densities at different positions in the spray. For example, by traversing along the long axis of a flat fan nozzle and recording the changing droplet density, it was possible to detect the edges of the spray fan and then calculate the fan angle. Similarly, by taking slices across the fan at intervals along the long axis, it was possible to estimate the thickness of the fan at each position and thus plot a 'footprint' of the spray. A variety of criteria were used to define the edges of the spray structure and the most repeatable was found to be the position at which the droplet density

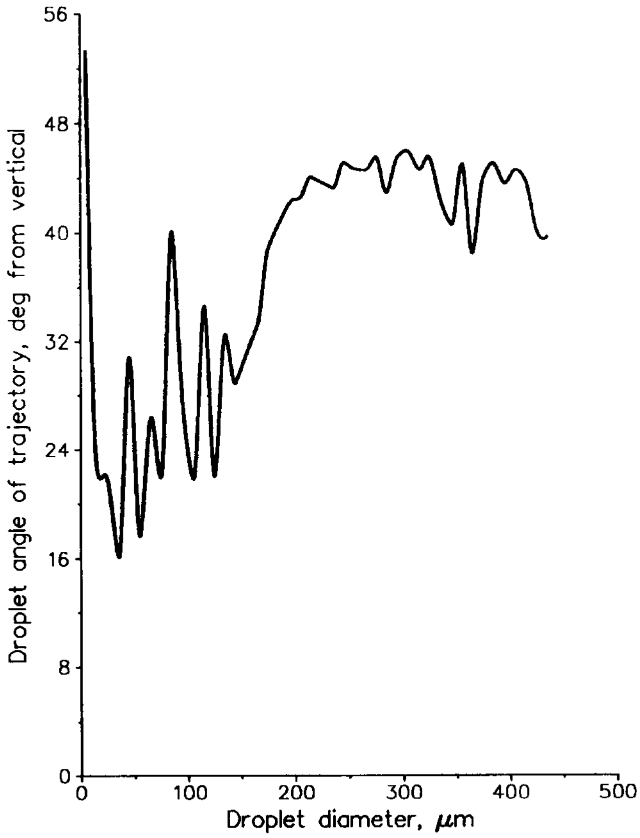

Figure 12. Droplet trajectories from an F110/0.6/3.0 nozzle spraying water at 3 bar, calculated from horizontal and vertical velocity components measured with the PDA at a position 350 mm below the nozzle and 350 mm along the long axis

is greater than 1% of the maximum droplet density, found in the centre of the spray. Other criteria have been used, such as a fixed droplet density of 0.5 droplet s^{-1}, which was used by Butler Ellis *et al.* (1997).

Flux calculations

It is possible to calculate the flux through the sample volume from the numbers and diameters of all the droplets recorded and the sample volume for each droplet size. However, with the PMS, only a fraction of the total number of droplets may be recorded in high density sprays, and with the 1-D PDA, the trajectory and slit effects can lead to large errors in volume measurements. The absolute flux cannot therefore be determined with either instrument. However, the liquid volume measured at positions in the spray as a percentage of the total volume can be estimated. Since the PMS does not sample uniformly across the spray fan, the percentage flux is likely to be less representative. *Figure 13* shows the percentage flux at positions within the spray measured with the PDA, PMS and a patternator for an F110/0.6/3.0 nozzle at 3 bar. Although there is some disagreement in the centre of the fan between PDA and the patternator, this is much less than was observed by Chapple and Hall (1993). Measurement of flux in agricultural sprays by PDA has not generally been reliable because the number of droplets observed is very variable and our experience suggests it can be

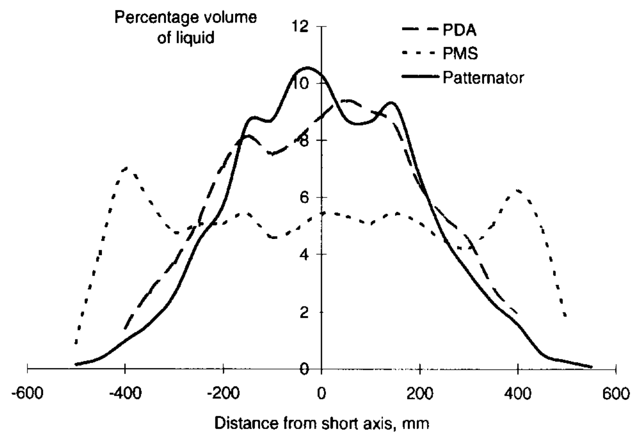

Figure 13. Percentage volume fluxes of liquid from an F110/0.6/3 nozzle spraying water at 3 bar, measured 350 mm below the nozzle at different positions along the long axis with the PMS and PDA scanning parallel to the short axis and with a patternator

affected by external factors such as background light levels and can also be influenced by the spray liquid. However, it can provide a useful estimate of flux variation across a spray fan when water is used, providing the measurements are made within a short space of time and with identical instrument settings. DualPDA, which eliminates some of the errors in PDA measurements, is likely to give more reliable absolute flux measurements (Tropea *et al.*, 1995). Results with PMS were of the expected form.

Measurement of entrained air velocities

The spray from flat fan nozzles interacts with the surrounding air, causing an air jet to become entrained within the spray fan. It is important to quantify this entrained air because it affects the interaction of the spray with other air flows.

Small droplets very quickly lose their initial momentum because of the effect of air drag, so that at some distance away from the nozzle the smallest droplets will be travelling at a velocity independent of their size, but dependent on the entrained air velocity (see *Figure 10*). Large droplets, however, will continue for longer at velocities greater than the air velocity. The small droplets can therefore be used to indicate the velocity of the entrained air, and this technique has been developed with PMS to measure air velocities within the spray fan (Miller *et al.*, 1996) by using droplets within the range 37–135 μm at distances of 350 mm below the nozzle and greater. Because the PDA can detect more of the smaller droplets and can cope with high spray densities, it is possible to use a range of 30–60 μm droplets and obtain velocities at very short distances from the nozzle. However, the velocities very close to the nozzle are not the same as the entrained air velocity because the small droplets have not lost their initial momentum and are still moving faster than the air (Miller, 1993). The position where droplet velocity is approximately the same as air velocity will depend upon the liquid flow rate and the initial droplet velocity, but for an F110/0.6/3.0 nozzle, the velocity of droplets up to 60 μm, measured with the PDA at 200 mm below the nozzle, was independent of their size, allowing entrained air velocities to be determined.

The effect of liquids on phase Doppler analysis

Phase Doppler analysis in forward scatter relies upon light passing through each droplet. Thus it is a prerequisite for the liquid to be translucent. The refractive index is required for calculation of droplet diameters, and therefore if spray liquids are based on solvents other than water, a knowledge of the refractive index is necessary. The calculation of diameter is not sensitive to the value of refractive index and therefore small changes, such as might be caused when adding a small quantity of a pesticide formulation, will not have a measurable effect.

A greater complication occurs when the droplets contain internal structure, such as emulsion droplets or air inclusions. These will interfere with the refraction of light through the droplet and cause an erroneous calculation of diameter. The addition of surfactants can cause air inclusions, particularly with twin fluid nozzles, and spray liquids made with many pesticide formulations are emulsions. Work carried out with a variety of active formulations and adjuvants showed that the distributions measured with both PMS and PDA can be similar, even when emulsion droplets, air inclusions or other interfaces were present, indicating that the PDA was measuring correctly. However, some combinations of ingredients led to such a high density of internal air/liquid or liquid/liquid interfaces that the PDA distribution began to show signs of inaccuracies. It is not known what determines whether the internal droplet structure will affect light scattering, and therefore it is important to take great care in measuring spray liquids other than water. The use of the PMS under these circumstances might lead to more reliable results.

Conclusions

Both droplet imaging (PMS) and phase Doppler analysis (PDA) are valuable tools in investigating and characterising the sprays from agricultural nozzles. Each instrument has its limitations and benefits, and used together can give useful results. In particular, the PDA is best for high density sprays and can readily detect small droplets. The PMS is appropriate for any spray liquid and can be used to define the maximum droplet size for setting the range of the PDA.

Care needs to be taken when sampling sprays with both instruments if the droplet size distribution is not constant throughout the spray, such as occurs with flat fan nozzles. It is important to ensure that a representative sample of droplets is measured and scanning parallel to the short axis at a number of horizontal positions was shown to produce the smallest variation in VMD. The number of droplets required for a representative sample depends upon the spray itself, the instrument used and the analysis technique. For flat fan nozzles, this was approximately 3000 droplets for the PMS, 13,000 droplets for the PDA and 8000 droplets for the PDA with maximum drop size determined by the PMS.

Because of the differences in measurement principles, the droplet size distributions recorded with the two instruments are not the same, with the PDA seeing a larger proportion of small droplets than the PMS and some erroneous large droplets. Recorded velocities were consistently lower with the PMS than with the PDA for all but the largest droplet sizes. The differences between the two instruments were smaller for sprays with a lower droplet density and for sprays with a narrower range of droplet sizes.

Measurements of droplet sizes and velocities can be used to determine other aspects of the spray, such as a horizontal cross-sectional footprint, droplet trajectories and entrained air velocities.

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