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MEASUREMENTS OF THE DROPLET VELOCITIES IN SPRAYS PRODUCED BY DIFFERENT DESIGNS OF AGRICULTURAL SPRAY NOZZLE

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ABSTRACT

Measurements of the vertical droplet velocity/size correlations for the reference nozzles used in an agricultural spray nozzle classification scheme showed good agreement between the results obtained with a new design of a double imaging instrument and a Phase Doppler Analyser. Similar measurements with two designs of conventional hydraulic pressure and three designs of air-induction nozzle showed substantial differences in the droplet size/velocity profiles for the different commercial nozzle designs. Velocity distributions with the air-induction nozzle designs were on average 40% less than those of the conventional hydraulic pressure nozzles. Droplet velocities increased with increasing pressure for all nozzles as expected with increases in the order of 23% for an increase in pressure from 3.0 to 5.0 bar for both the conventional and air induction nozzles. Spray fan angle was also indicated as an important parameter influencing droplet velocities. Changes in spray liquid properties that would be typical of different agricultural chemical applications showed some differences in droplet velocities from the nozzles studied with the largest differences of up to 50% measured with a conventional nozzle. Measurements of the airborne flux within a spray made by both the imaging system and conventional collection sampling techniques showed also good agreement.

1. INTRODUCTION

Information relating to the velocity of spray droplets produced by agricultural spray nozzles together with data relating to the droplet size and flux distributions in the spray is important if the behaviour of such sprays in complex air flows is to be understood. Droplet velocities close to a nozzle are an important input to physical models predicting droplet trajectories [1] and the risk of drift [2, 3] from agricultural spray applications. Measurements made with a two-dimensional optical imaging probe [4, 5] showed that, typically, droplets from agricultural hydraulic pressure flat fan nozzles had a size/velocity profile 350 mm below the nozzle in which the small droplets, up to 135 µm in diameter could be assumed to be travelling at the velocity of the entrained air. Larger droplets were decelerating from a release velocity in the range 20-25 m/s. Miller et al., [4] used such measurements to develop a model to describe the entrained air velocities at different positions within a flat fan spray.

The development of the Phase Doppler instrument provided a measurement system that would operate with greater confidence in regions of high droplet number density such as found close to a nozzle. Comparative studies [6] showed reasonably good agreement for size/velocity profiles measured with both the Phase Doppler and the direct imaging systems. Much of the development of agricultural spray nozzles over the last two decades has addressed the issue of drift control including the development and now commercial popularity of the air-induction nozzle design. Sprays from air-induction nozzles give relatively large droplets with air inclusions and there is evidence that the presence of such air inclusions influences the behaviour of the Phase Doppler instrument and certainly increases the signal rejection rate. The Phase Doppler instrument also has difficulties in analysing the sprays from liquids with emulsions that are commonly used for agricultural chemical applications.

A new spray analyser system has been developed (Oxford Lasers "VisiSizer") in which images from a pulsed laser are compared to identify the positions of droplets within two successive images so that both size and velocity within a measurement plane can be calculated. This paper reports the results of measurements with this system and compares the results obtained with other published and unpublished data.

2. MEASUREMENTS WITH REFERENCE FLAT FAN NOZZLES

The droplet size distribution in an agricultural spray is described by a classification system [7] that now uses reference stainless steel flat fan nozzles to define the boundaries between spray quality classes. These reference nozzles are:

- a 110° flat fan "03" nozzle size (FF110/1.2/3.0) operating at a pressure of 3.0 bar to define the boundary between medium and fine spray qualities;
- a 120° flat fan "06" nozzle size (FF120/1.96/2.0) operating at a pressure of 2.0 bar to define the boundary between coarse and medium spray qualities;
- a 80° flat fan "08" nozzle size (FF80/2.92/2.5) operating at a pressure of 2.5 bar to define the boundary between coarse and very coarse spray qualities.

Measurements of the droplet size and velocity distributions in the sprays generated by these reference nozzles spraying water were made with the double imaging system and the results compared with equivalent data obtained with a Phase Doppler analyser. Nozzles were mounted on a computer-controlled x-y transporter system 350 mm above the sampling laser and the transporter programmed to move the nozzles on a 20 mm grid through the short axis of the spray at a speed of 20 mm/s. The double imaging system used short pulse illumination source to eliminate motion blur and illuminate the area behind the droplets using advanced speckle free diffuser arrangement. A 4.0 megapixel CCD camera and lens set up, with lens option 3, magnification 3 and 20.4 µs between image frames, was used to acquire images. VisiSizer software with fully integrated system control was used to analyse the images. VisiSizer software used image thresholds to identify the droplets in the image, once identified the VisiSizer software used advanced algorithms to determine droplet size and tracking droplet displacement between two images to determine droplet velocity information.

The results are summarised in Tables 1 and 2 and the measured droplet size/velocity profiles plotted in Figure 1. The volume median diameters (VMD) measured with the values from the Phase Doppler analyser although given that both systems were recording a temporal sample the level of agreement may have been expected to be better. The greatest discrepancies were with the largest output nozzle and in the estimation of the percentage of spray volume in small droplet sizes (<100 µm in diameter) for all of the nozzles. These results suggest that the imaging system is measuring a wider range of droplet sizes particularly with the higher output nozzles where the percentage of spray volume in droplets <100 µm in diameter is greater than that measured by the Phase Doppler analyser but the volume median diameter is lower. This suggestion was also supported by visual inspection of the droplet size distributions measured by both instruments with the Phase Doppler instrument recording a higher peak of at about the volume median diameter.

Spray fan angles were estimated from the flux distributions measured across the sampling grid. A smoothed distribution was fitted to measured flux values and the spray fan angle estimated from the interpolated width of the spray pattern accounting for 99% of the measured spray flux. Estimated spray fan angles (Table 1) based on measurements with the two systems were in reasonable agreement and in line with expectation based on manufacturers data.

The droplet velocities (Table 2) and droplet size/velocity profiles (Figure 1) measured by the two systems showed a high level of agreement. The mean liquid velocity calculated from the measured flux and velocities across the range of droplet sizes generally increased with increases in nozzle flow rate as expected. Mean liquid velocities for the FF120/1.96/2.0 nozzle were less than for the FF110/1.2/3.0 even though the liquid flow rate was higher. This was probably due to a combination of effects relating to the wider spray fan angle (velocities plotted are in the vertical direction only) and the lower pressure at which this nozzle was operated.

Table 1. Droplet size data for the stainless steel reference nozzles.

Nozzle	Pressure, bar	D_{50} (VMD) µm		% spray volume <100 µm diameter		Estimated fan angle, degrees	
		VisiSizer	PDA	VisiSizer	PDA	VisiSizer	PDA
FF110/0.49/4.5	4.5	152.9	172.9	22.4	11.2	110	116
FF110/1.20/3.0	3.0	279.9	257.3	5.4	2.9	110	109
FF120/1.96/2.0	2.0	340.6	349.8	3.6	1.5	123	126
FF80/2.92/2.5	2.5	457.6	391.8	1.9	0.7	79	80

Table 2. Droplet velocity data for the stainless steel reference nozzles.

Nozzle	Pressure, bar	Mean liquid velocity, m/s		Mean velocity (m/s)for droplet sizes					
				40-60 µm		290-310 µm		490-510 µm	
		VisiSizer	PDA	VisiSizer	PDA	VisiSizer	PDA	VisiSizer	PDA
FF110/0.49/4.5	4.5	2.66	3.35	1.80	1.89	7.67	5.11	N/A	N/A
FF110/1.20/3.0	3.0	7.47	7.62	2.38	2.61	7.68	8.98	13.84	14.12
FF120/1.96/2.0	2.0	5.97	6.51	2.27	2.50	5.57	6.68	7.74	7.42
FF80/2.92/2.5	2.5	12.51	12.01	3.17	4.01	10.99	11.40	13.18	13.32

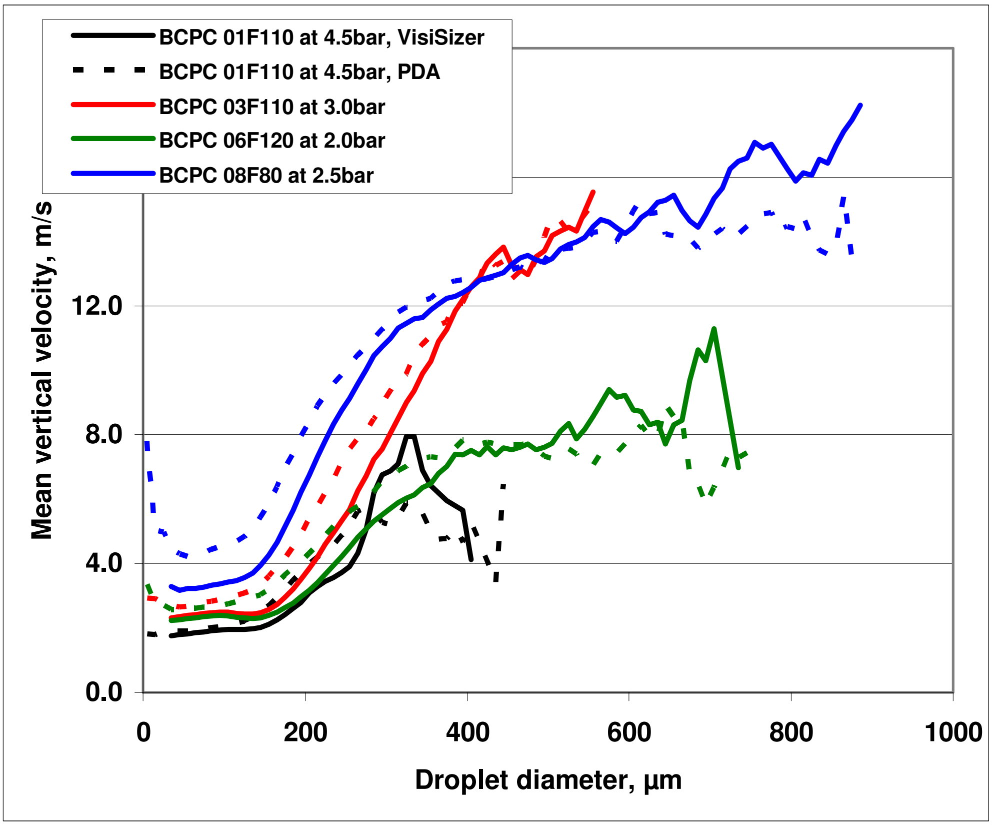

Figure 1. Droplet size/velocity profiles measured for the reference hydraulic pressure flat fan agricultural nozzles made in stainless steel.

3. MEASUREMENTS COMPARING CONVENTIONAL AND AIR-INDUCTION AGRICULTURAL SPRAY NOZZLES

Measurements were made using the double imaging system in the sprays from two designs of conventional hydraulic pressure flat fan nozzle and three designs of air-induction nozzle all with comparable flow rate and spray fan angle specifications and operating at pressures of 3.0 and 5.0 bar. The results (Table 3) show that the mean droplet sizes for the air-induction nozzles were substantially larger than for the conventional designs as expected probably due to the presence of air-inclusions at the point of spray formation. Increasing pressure from 3.0 to 5.0 bar reduced the mean droplet size (as VMD) for conventional nozzles by approximately 9% and increased the percentage of spray volume in droplets <100 µm in diameter by some 48%.

The percentage of spray volume in droplets <100 µm in diameter was significantly lower for the air-induction nozzles with mean reductions of 87 and 81% at pressures of 3.0 and 5.0 bar respectively. This is consistent with this nozzle design giving substantial drift reductions when used in conjunction with boom sprayers [8]. Estimated spray fan angles were broadly inline with expectations based on manufacturers published specification although there is more variation than might have been expected. The Lechler conventional nozzle gave a spray fan angle significantly lower than expected while the spray from the TeeJet nozzle was wider than expected.

Droplet velocities for a given size of droplet in the sprays from the air-induction nozzle were approximately 40% less than for the equivalent droplet size from the conventional nozzles (Table 3) at both operating pressures. It can be seen however, that the mean liquid velocity from the two nozzle designs were comparable indicating an equivalent momentum in the spray from an air-induction nozzle to that in the spray from a conventional hydraulic pressure flat fan nozzle. The droplet size/velocity profiles for these nozzles at the two pressures (Figures 2 and 3) show the expected form with lower velocities for droplets in the spray from the air-induction nozzles. Droplets in the sprays from the air-induction nozzle giving the largest droplet size gave the lowest droplet velocities and this is consistent with a higher level of air inclusions in the spray from this nozzle design. The presence of larger droplet sizes in the sprays from the air-induction nozzle design can also be seen in Figures 2 and 3. The plotted size/velocity relationships (Figures 1-3) show more variation in the mean velocities for the larger droplet sizes in the distribution and this is due to the lower number of droplets in these larger size ranges.

The results show not only differences between droplet size and velocity distributions between the two different designs but also considerable differences between different versions of the same nozzle design. This is consistent with work reported by other authors for air-induction nozzle designs [9, 10] but the differences in the droplet velocity distributions from the two conventional nozzles used in this study is larger than expected.

Table 3. Droplet sizes and velocities in the sprays from conventional and air-induction agricultural spray nozzles.

Nozzle	Pressure, bar	Flow, L/min	VMD, µm	% of vol. in droplets <100 µm diameter	Estimated spray angle, degrees	Mean liquid velocity, m/s	Mean velocity (m/s) for droplet sizes		
							40-60 µm	290-310 µm	490-510 µm
Lechler LU120-03	3.0	1.17	256	5.93	94	6.91	2.62	8.24	14.79
TeeJet XR110 03	3.0	1.17	262	6.19	119	5.22	2.01	6.40	7.83
Billericay BubbleJet 03	3.0	1.19	431	1.23	105	6.08	1.74	4.49	7.17
Lechler IDK 120 03	3.0	1.14	489	0.85	118	5.85	1.57	3.86	5.96
TeeJet AI 110 03 VS	3.0	1.18	628	0.36	105	6.03	1.38	3.62	6.28
Lechler LU120-03	5.0	1.49	231	9.26	97	8.20	2.99	11.60	n/a
TeeJet XR110 03	5.0	1.50	240	8.63	121	6.36	2.46	7.47	n/a
Billericay BubbleJet 03	5.0	1.53	359	2.57	111	6.71	2.09	5.87	8.75
Lechler IDK 120 03	5.0	1.46	406	1.91	115	6.51	1.86	4.59	7.52
TeeJet AI 110 03 VS	5.0	1.51	546	0.72	115	7.14	1.61	4.58	6.99

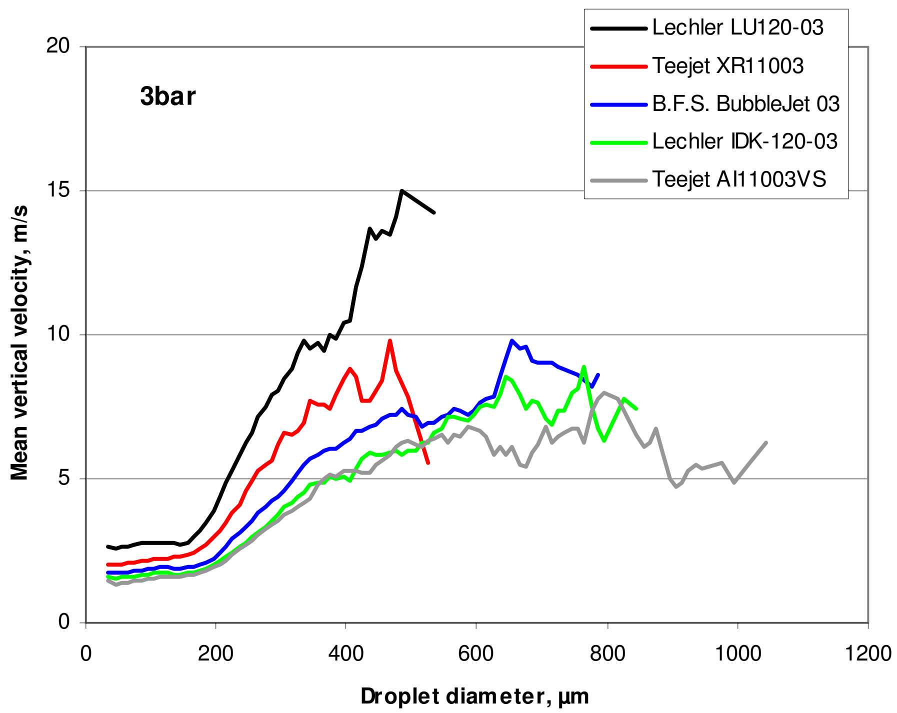

Figure 2. Droplet size/velocity profiles for two conventional and three air-induction nozzle designs operating with water at a pressure of 3.0 bar.

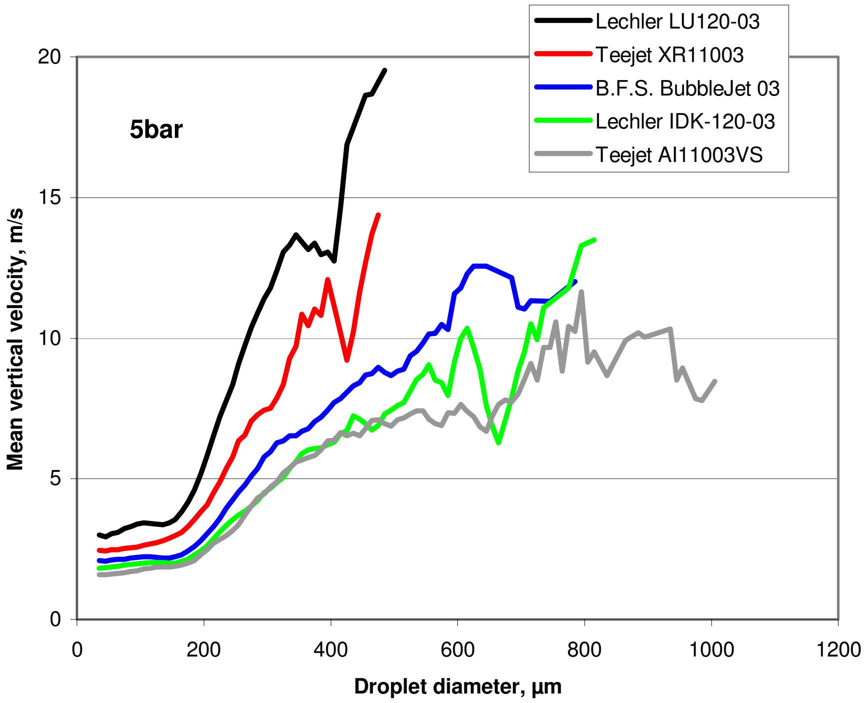

Figure 3. Droplet size/velocity profiles for two conventional and three air-induction nozzle designs operating with water at a pressure of 5.0 bar.

It should be noted that the conventional hydraulic pressure flat fan nozzles used in this study were of a design that enables spray characteristics, particularly the volume distribution pattern to be maintained over a wide range of operating pressures and are commonly referred to as extended range or variable pressure nozzles.

4. MEASUREMENTS WITH DIFFERENT SPRAY LIQUIDS

Most studies of spray formation and transport relating to agricultural pesticide application use a spray liquid containing a non-ionic surfactant and, if needed, a soluble tracer dye. However, it is known that the physical properties of the spray solution do influence spray formation processes, the droplet size distribution, volume distribution pattern and the risk of drift [11, 12]. Measurements were therefore made with two liquids representative of different agricultural chemical mixtures as follows:

- a mixture of water and 1.0% methylated rapeseed oil (842 g/l) adjuvant (Rigger – IntraCrop – a division of Brian Lewis Agriculture Ltd) – Liquid A in Table 4 and on Figures 4 and 5;
- a mixture of water and 0.5% ethoxylated tallow amine (822 g/l) surfactant (Frigate – ISK BioSciences Ltd) – Liquid B in Table 4 and on Figures 4 and 5.

Two nozzles were used as being representative of a conventional design (TR120-02 – Hypro Ltd) and an air-induction nozzle (BubbleJet 02 – Billericay Farm Services Ltd) both operating at a pressure of 3.0 bar to give a flow rate of 0.8 L/min. The results, summarised in Table 4, showed that Liquid A containing the methylated rapeseed oil sprayed through the conventional nozzle gave a larger droplet size than when spraying water whereas Liquid B containing the ethoxylated tallow amine gave a slightly smaller mean droplet size. For the air-induction nozzle, the largest droplet size was measured when spraying water, with smaller mean sizes when spraying Liquid A and particularly Liquid B. The results for both nozzle designs spraying water and Liquid A containing the methylated rapeseed oil are consistent with expectations based on other published work [11]. However, it was expected that Liquid B would substantially reduce the mean droplet size with the conventional nozzle and would increase the mean size with the air-induction nozzle because of the increase in the air included volume. This was based on Liquid B being a soluble surfactant with the main effect of reducing dynamic surface tension. It is likely that the results obtained can be explained by the detailed components in the formulation of the adjuvant used in Liquid B giving rise to competing effects influencing the spray formation with the air-induction nozzle a discussion of which is beyond the scope of this paper.

Spray liquid properties had a significant effect on droplet velocities from both nozzle designs (Table 4 and Figures 4 and 5) with the effects again being different for the two designs. For the conventional nozzle, operation with water and with Liquid B gave similar size/velocity profiles (Figure 4) and mean liquid velocities. Spraying Liquid A gave higher mean liquid

Table 4. Droplet sizes and velocities in the sprays from a conventional and air-induction nozzle operating with two different spray liquids.

Nozzle	Spray liquid	VMD, μm	% of vol. in droplets <100 μm diameter	Estimated spray angle, degrees	Mean liquid velocity, m/s	Mean velocity (m/s) for droplet sizes		
						40-60 μm	290-310 μm	490-510 μm
Hypro TR120-02	Water	214	11.25	120	3.68	2.20	4.86	n/a
	Liquid A	254	4.17	129	5.42	1.57	6.62	n/a
	Liquid B	211	12.70	120-	3.56	2.09	4.60	n/a
Billericay BubbleJet 02	Water	452	1.03	101	6.46	1.43	4.89	7.39
	Liquid A	437	0.68	100	6.51	1.43	5.17	7.48
	Liquid B	375	3.38	90	4.55	1.43	3.20	6.29

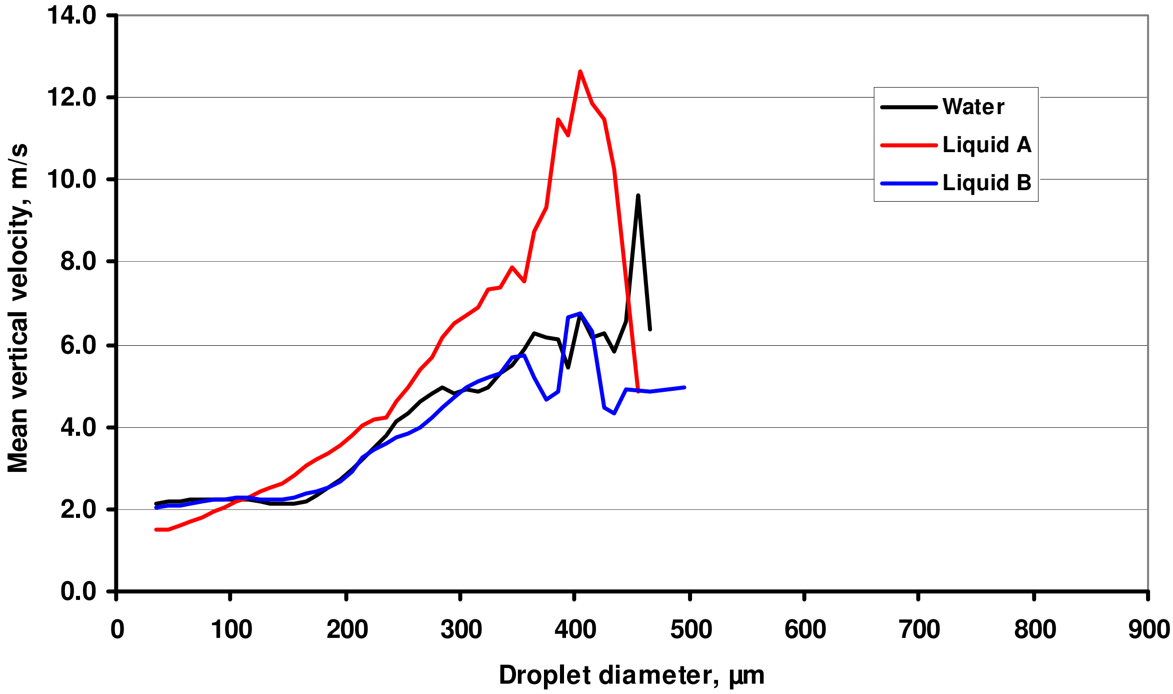

Figure 4. Droplet size/velocity profiles for a design of conventional nozzle operating with three spray liquids typical of agricultural pesticide application.

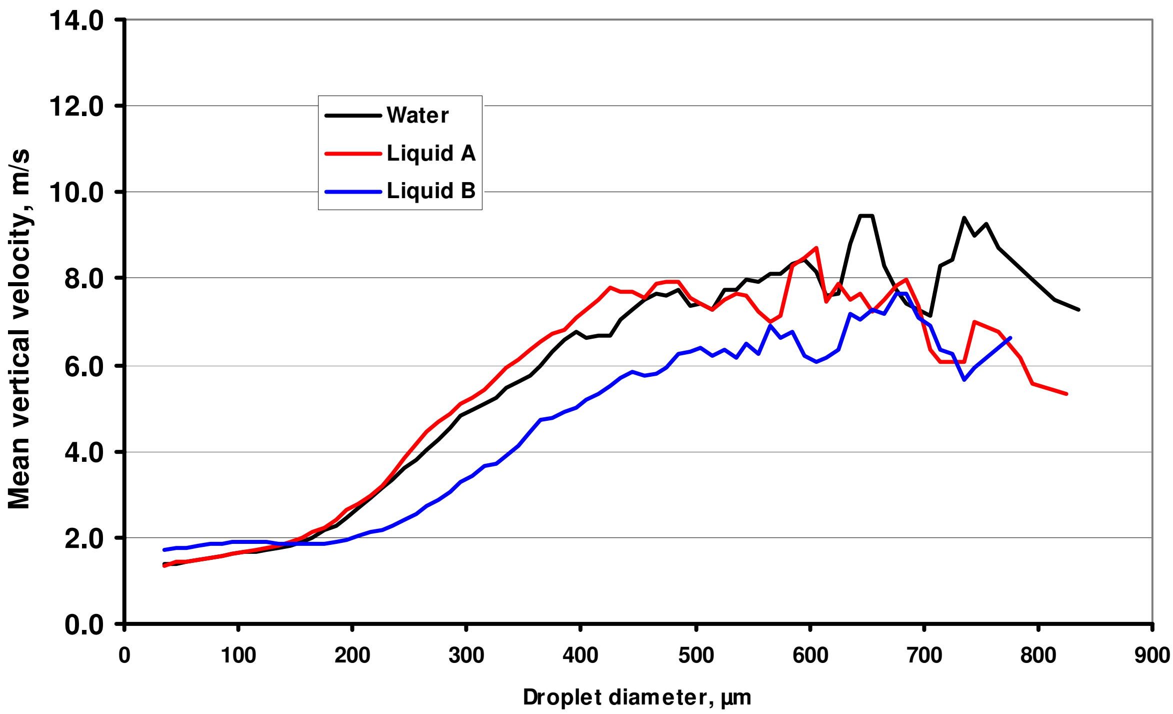

Figure 5. Droplet size/velocity profiles for a design of air-induction nozzle operating with three spray liquids typical of agricultural pesticide application.

velocities and higher velocities at defined droplet sizes. For the air-induction nozzle droplet velocities when spraying water and Liquid A were comparable but spraying Liquid B gave significantly lower droplet velocities.

5. MEASUREMENT OF SPRAY FLUX

The measurement of spray flux with a droplet size analysis system is important not only as a basis for direct flux measurement but also to ensure that measured size distributions within a spray account for the flux distributions within that spray. Comparisons of the flux measured with the Oxford Lasers "VisiSizer" were made with direct measurements made with a single channel collection system that has been designed for use in conjunction with an x-y nozzle transporter to determine the spray volume distribution patterns from different nozzle configurations. Measurements were made in the spray from a 110^o conventional flat fan nozzle spraying water at a pressure of 3.0 bar. Samples were taken close to the nozzle and therefore close to the position at where the liquid sheet had been measured as being broken into droplets. This was expected to be a difficult sampling environment for the imaging system because of the high velocity of droplets and the shape of the droplets close to the position of formation. A series of static nozzle measurements were made with both systems corresponding to a 25 mm wide section through the short axis of the spray at the defined positions. For the imaging system, this involved a number of point measurements such that the results could be combined to give a comparative value to that measured directly with the collection system. Measurement positions were chosen to give a wide range of spray fluxes in the measurement zones.

The results shown in Figure 6 show excellent agreement for fluxes measured with the two systems up to flux levels of 2.5 mL/s. At flux levels greater than this, the imaging system started to underestimate airborne fluxes as expected probably due to the increased probability of obscured droplets within the sampling volume.

6. CONCLUSIONS

The double imaging spraying system is a useful approach to the measurement of droplet size and velocity distributions in a wide range of sprays. Results from this instrument are in reasonable agreement with those from comparable techniques including Phase Doppler analysis.

Measurements in the sprays from agricultural air-induction nozzle designs showed that although the velocities of defined droplet sizes were in the order of 40% less than those from comparable conventional hydraulic pressure nozzles, the mean liquid velocities and hence the momentum in the spray from both nozzle designs were similar. The results of the measurements reported here showed that nozzle performance was a function of design, operating pressure and spray liquid properties with the performance of the air-induction nozzle design being explained by the presence of air-included droplets within the spray.

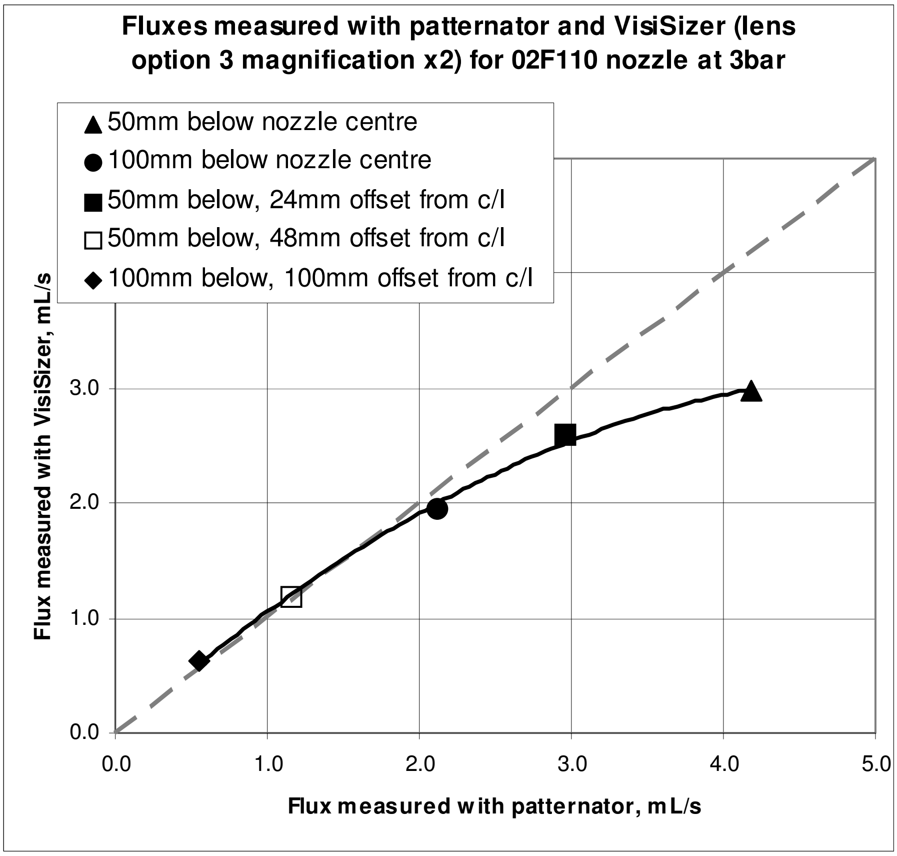

Figure 6. Measured fluxes with the imaging system and direct volume capture method (patternator).

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