PDPA Laser-Based Characterisation of Agricultural Spray Nozzles

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ABSTRACT

Characterising agricultural sprays is a critical factor when investigating and predicting the spray drift, deposition on plants, spray coverage and biological efficacy. Hence to underpin a research project to predict spray drift, a measuring protocol to enable consistent characterisation of spray from nozzles used in agriculture using a Phase Doppler Particle Analyser (PDPA) was developed. The set-up measures droplet sizes and velocities based on light-scattering principles. It comprises a controlled climate room, a spray unit, a three-dimensional automated positioning system, and an Aerometrics PDPA 1D system.

This paper presents a detailed description of the measuring set-up along with some experimental results. In total, 32 nozzle-pressure combinations were tested and spray quality categorized based on the British Crop Protection Council (BCPC) classification scheme using the measured droplet size spectra . The results confirmed the importance of nozzle type and flow rate on droplet size and their velocity The measurements will be used as an input for a Computational Fluid Dynamics drift-prediction model and to categorize nozzles based on their relative driftability.

Keywords: Agricultural sprays, Phase Doppler Particle Analyser, spray droplet characteristics, nozzle classification, spray drift predictions, spray quality.

1. INTRODUCTION

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

Over recent years, several techniques using laser instrumentation have been developed to determine droplet characteristics. For example laser diffraction (e.g. Malvern laser) (Barnett and Matthews, 1992; Butler Ellis and Bradley, 2002), the optical area probe technique (e.g. Particle Measuring System) (Combellack et al., 2002) and the Phase Doppler Particle Analyzer (e.g. Aerometrics) (Farooq et al., 2001).

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

The optical area probe technique allows size and velocity to be determined of individual droplets passing through a small measuring volume. Generally, the Particle Measuring System instrument measured a significantly greater volume median diameter compared to the Malvern, except for very low flow rates (Arnold, 1987). The PDPA gave consistently lower values for the volume median diameter and lower percentages of spray volume in droplets less than 100 µm in diameter than the PMS (Tuck et al., 1997).Besides different measuring techniques, there are important differences between different researches in measuring set-up and protocol (e.g. nozzle height, scan pattern, sampling strategy, data processing, etc.) which have an effect on the measuring results (Chapple and Hall, 1993; Butler Ellis et al., 1997).

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

Because of the differences between techniques and protocols, a detailed description of how the Aerometrics PDPA was set-up, as well as the measuring protocol, are presented along with the results of 32 commonly used nozzle-pressure combinations.

2. MATERIALS AND METHODS

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

2.1 Spray Unit

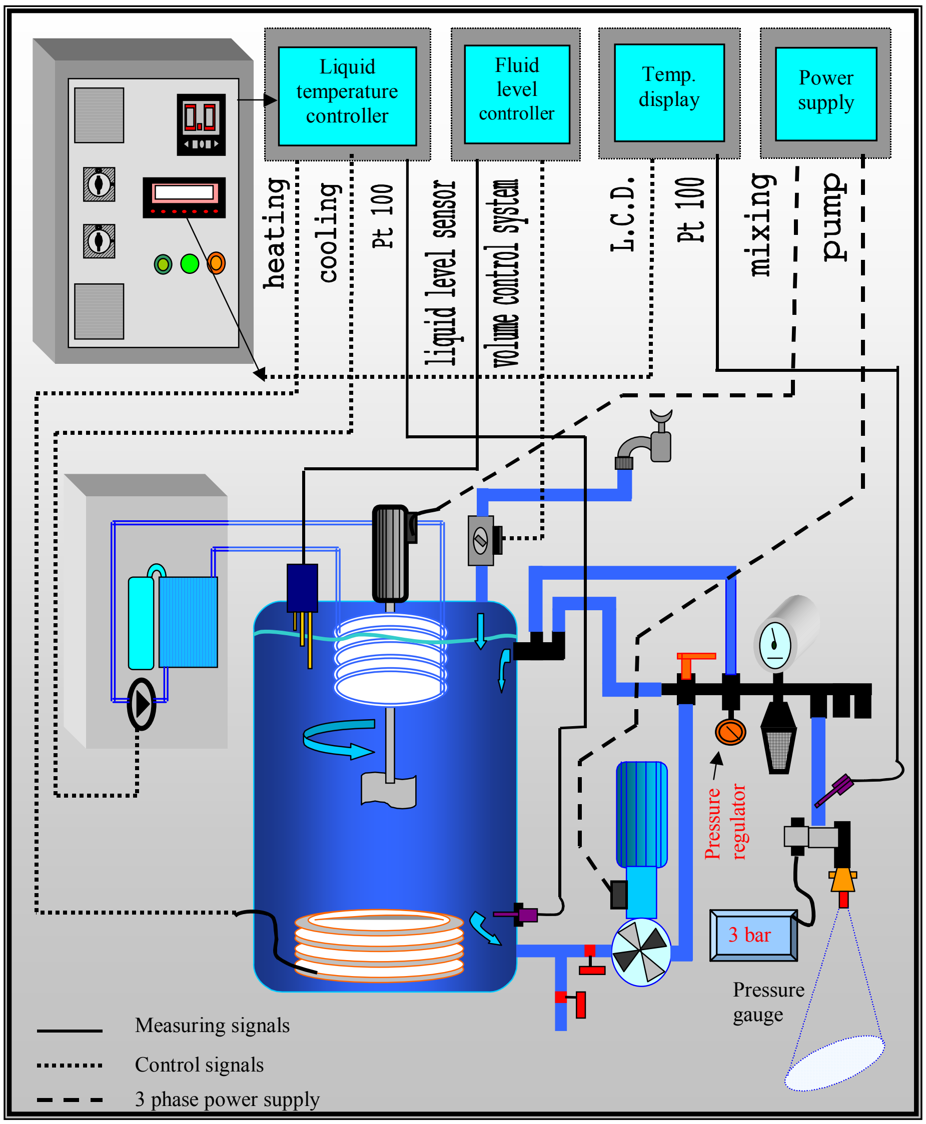

Figure 1. Schematic overview of the spray unit.

The spray unit consists of the following parts, as presented in figure 1:

- A 100 litre insulated spray liquid tank with a fluid level control system that can be switched off if an active ingredient is used.
- A liquid temperature control system with a Pt100 temperature sensor at the exit of the liquid tank, just before the spray nozzle; a PID regulation system, a heating resistor (with a capacity of 6 kW), a water cooling unit, and mechanical as well as a hydraulic mixing of the tank contents. In case of continuous spraying, a fluid temperature range from 5 to 50 °C is feasible.
- A vertical in-line centrifugal pump that can deliver 1.4 $l.s^{-1}$ at a pressure of 6.6 bar with a maximum capacity of 5 $m^3.h^{-1}$.
- A manually adjustable pressure regulator and a digital pressure gauge with a resolution of 0.01 bar.

2.2 Three-dimensional Positioning System

When measuring droplet characteristics, the PDPA measurements are made at a fixed point and the nozzle is moved using an automated XYZ-transporter with a traverse range of 2.0 m by 2.2 m (fig. 2). The XY-movement is achieved using two Siemens Simodrive Posmo A motors and is controlled by a Siemens Programmable Logic Controller (PLC) with a control panel. These motors have a rating of 300 W and are equipped with a 1/49 reducer to optimise the accuracy of the positioning system.

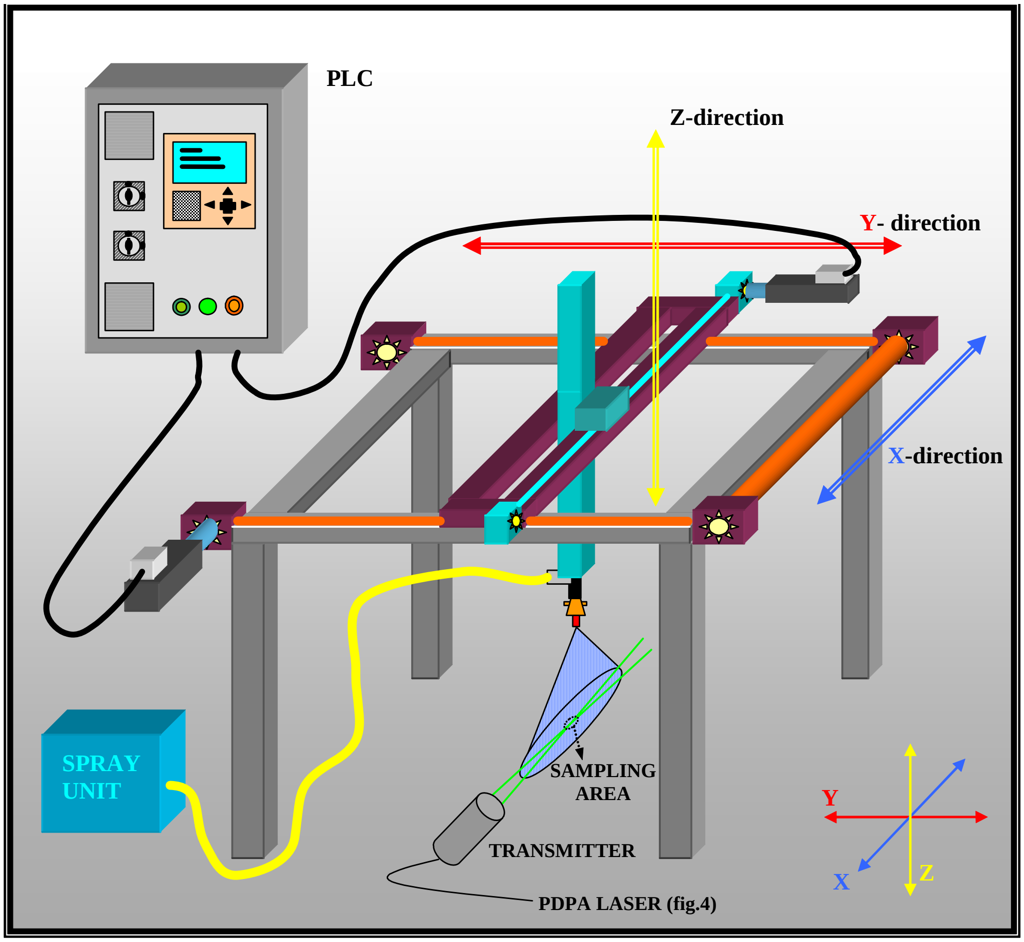

Figure 2. Schematic overview of the automated XYZ-transporter with the intersecting laser beams and sampling area.

The vertical distance between the nozzle and the measuring point (Z-direction) can be adjusted manually from 0 to 0.90 m. The measuring point is located at a height of 0.80 m above the floor to avoid measurement errors due to rebounding droplets.
Different scan patterns can be carried out, each one with the start and end position of the spray nozzle in the centre of the XY-rectangle straight above the measuring point. The possible scan patterns are:

- Free manually-controlled movement of the spray nozzle
- Movement of the spray nozzle to a certain XY position in which the nozzle is stationary for a definable period of time
- Scanning of a defined rectangular pattern as illustrated in figure 3 to effect a 'complete' scan of the spray cloud. The x, Δx, y and Δy can be chosen as desired. Moreover, there are two possible ways of scanning: (1) continuous, at a constant definable speed v without stops and (2) discontinuous, with stops at distance intervals Δx for a definable period of time

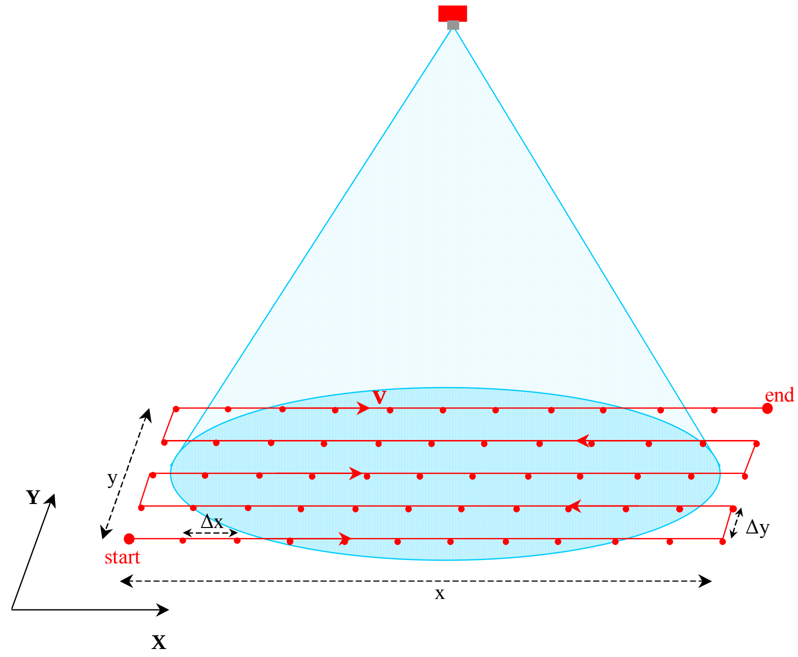

Figure 3. Scan trajectory.

2.3 Controlled Climate Room

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

2.4 PDPA Optical Laser Equipment

The PDPA laser used in this research was an Aerometrics PDPA 1D (TSI, Minneapolis). The system is comprised of several components (fig. 4) i.e. an Argon-Ion laser, a fibre drive, a fibre-optic coupler, a fibre-optic transmitter and receiver, a Real-Time Signal Analyzer (RSA), and DataVIEW-NT 2.0.4.0 software. With this apparatus, droplets pass through a small sampling volume (46.8 mm by 0.468 mm), scattering light by refraction. Velocity measurement with the 1D system used, is limited to the dominant vertical direction.

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

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

$$\delta_f = \frac{\lambda}{2.\sin(\frac{\theta}{2})} \tag{1}$$

This results in a fringe spacing δ_f of 25.7 µm when λ is 514.5 nm and θ is 1.146°, derived from the initial beam spacing of 0.01 m and the focal length of 0.5 m. When a spherical particle crosses the intersection of both laser beams, the rays enter the sphere at different angles. Besides, the particle has a different index of refraction than the surroundings. Hence, the rays have to travel along different optical paths with different lengths. Because of the different optical path lengths, the light waves are shifted relative to each other. These phase shifts result in an interference pattern in the field surrounding the particle (Bachalo and Houser, 1984). Interference fringes are bright and dark lines produced by the constructive and destructive interference of the intersecting light waves. If a particle is moving with a velocity v ($m.s^{-1}$) through the intersection of the beams, light will scatter with a frequency f_d (s^{-1}). This frequency f_d is equal to the velocity v ($m.s^{-1}$) divided by the fringe spacing δ_f (m). Hence, frequency and particle velocity are related through the following relation:

$$v = f_d \cdot \frac{\lambda}{2.\sin(\frac{\theta}{2})} \tag{2}$$

The fibre-optic receiver collects the scattered laser light. The instrument was operated in the near-forward scatter mode (first order of refraction) with the receiving optics set at 30° to the incident beam (Tuck et al., 1997). This produces the highest sizing sensitivity and the most satisfactory results for transparent liquids like water. The fibre-optic receiver consists of two lenses with focal lengths of 300 mm (front lens) and 250 mm (back lens). The receiver lens system focuses the light onto a spatial filter to limit the extent of the sampling area. Light passing through the slit (slit aperture: 100 µm) is collimated by the collimating lens onto the mask. The mask effectively partitions the receiver lens into four regions. These regions become the three detectors used by the PDPA to determine size and velocity. After passing through the mask, light is directed by the prism pack to the three photomultiplier tubes (PMT's) which convert the light signals into electrical signals to be processed for velocity and size information by the Real-Time Signal Analyzer 3100-P (RSA). This RSA is designed for real-time processing of laser Doppler velocimeter and phase Doppler signals based on the discrete Fourier transform method. Signals are detected, processed and validated simultaneously and continuously. Each PMT produces a signal with a frequency proportional to the particle velocity. The phase shift between the signals from two different PMT's is proportional to the size of the spherical particles (Bachalo and Houser, 1984; Borys, 1996).

Finally, DataVIEW-NT 2.0.4.0 software contributes to the overall ease of use of the system and gives complete control over the presentation and acquisition of the data.

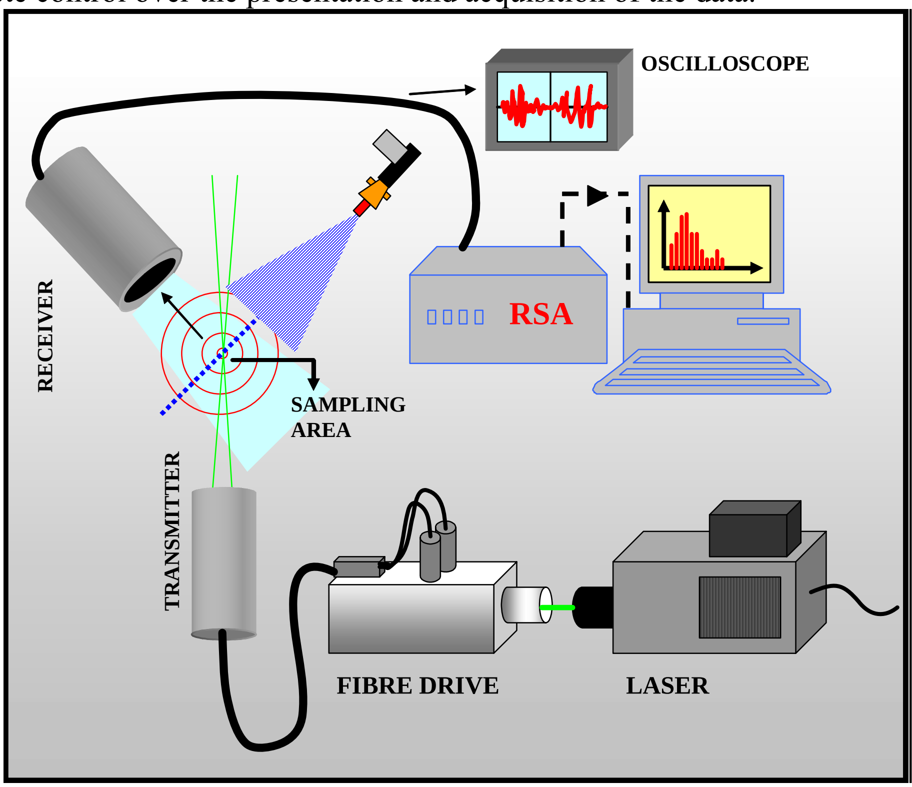

Figure 4. Schematic overview of the PDPA optical laser instrument.

Measurement ranges for velocity and diameter can be changed through variations of optical set-up, laser beam separation, and lens focal lengths of the transmitting and receiving optics. Settings on the instrument were chosen to cover a size range of 9 to1000 µm, corresponding respectively with phase shifts of 3° to 350°.

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

The PDPA instrument requires no calibration because the droplet size and velocity are dependent only on the laser wavelength and optical configuration. PDPA measurements are not based upon the scattered light intensity and, consequently, are not subject to errors from beam attenuation or deflection which occur in dense particle environments. Figure 5 shows pictures of the full measuring set-up.

Figure 5. Some pictures of the PDPA laser measuring set-up.

2.5 Measuring Protocol

Before any PDPA laser measurements, the flow rate of each nozzle is tested at a pressure of 3 bar by the accredited Spray Technology Lab (Beltest 259-T ISO 17025) of the Institute for Agricultural and Fisheries Research (ILVO) (Goossens and Braekman, 2003). A maximal deviation of ± 2.5% is allowed compared to the prescribed nominal flow rate.

For the PDPA measurements in these tests, three nozzles were selected for each nozzle-pressure combination and each nozzle is tested three times. This makes a total of 9 measurements for each nozzle-pressure combination carried out in random order. Each scan yielded data for at least 10000 droplets as recommended by Adams et al. (1990). The British Crop Protection Council

(BCPC) reference nozzle fine-medium (Lurmark F 110 03 at 3 bar) was used as a reference nozzle to check for the repeatability the measuring equipment before and after each measuring session (Southcombe et al., 1997). All measurements were made spraying water at a temperature of approximately 20°C. Environmental conditions were kept constant at a temperature of 20 °C and a relative humidity between 60 and 70%. The nozzle was positioned 0.50 m above the measuring point of the PDPA.

To enable the whole of the spray fan to be sampled, the nozzle was mounted on the transporter. A different scan trajectory (fig. 3) was programmed depending on the type of nozzle, i.e. 110° flat fan nozzle, 80° flat fan nozzle or 80° cone nozzle. All measurements were carried out through the long axis of the spray cloud at a constant scan speed (Table 1).

Table 1. Characteristics of the scan trajectory for the different nozzle types

	Scan speed v ($cm.s^{-1}$)	x (m)	y (m)	Δy (m)	Measuring time (s)
110° flat fan nozzles	2.50	1.50	0.40	0.10	316
80° flat fan nozzles	1.66	1.00	0.40	0.10	324
80° cone nozzle	3.00	1.00	1.00	0.10	400

3. RESULTS AND DISCUSSION

In total, 32 nozzle-pressure combinations (288 measurements) were taken (Table 2).

Table 2. Overview of the tested nozzle-pressure combinations

Nozzle	Pressure (bar)	Nozzle	Pressure (bar)	Nozzle	Pressure (bar)
*Delavan LF 110 01**	*4.5*	Albuz API 110 06	3.0	Hardi ISO F110 03	2.0; 3.0; 4.0
*Lurmark F 110 03**	*3.0*	Albuz AXI 110 02	3.0	Hardi ISO F 110 04	3.0
*Lechler LU 120 06**	*2.0*	Albuz AXI 110 04	3.0	Hardi ISO F 110 06	3.0
*TeeJet 80 08**	*2.5*	Albuz AXI 110 06	3.0	Hardi ISO LD 110 02	3.0
*TeeJet 80 15**	*2.0*	Albuz ADI 110 02	3.0	Hardi ISO LD 110 03	3.0
Albuz ATR80 blue	3.0	Albuz ADI 110 04	3.0	Hardi ISO LD 110 04	3.0
Albuz ATR80 green	3.0	Albuz AVI 110 02	3.0	Hardi ISO Injet 110 02	3.0
Albuz ATR80 orange	3.0	Albuz AVI 110 04	3.0	Hardi ISO Injet 110 03	3.0
Albuz API 110 02	3.0	Albuz AVI 110 06	3.0	Hardi ISO Injet 110 04	3.0
Albuz API 110 04	3.0	Hardi ISO F 110 02	3.0	Hardi ISO Injet 110 06	3.0

*BCPC reference nozzles

The characteristics presented in this table and in the figures are:

- BCPC: BCPC spray quality class based on droplet size spectra of the reference nozzles.
- $D_{v0.1/0.9}$: 10/90 percent of the total volume is made up of drops with diameters smaller than these values (µm).
- VMD = $D_{v0.5}$: Volume Median Diameter, 50 percent of the total volume (or mass) is made up of droplets with diameters smaller than this value (µm).
- $V_{100/200}$: Percentage of total volume of droplets smaller than 100/200 µm (%).
- D_{10}, D_{20}, D_{30}, D_{32}: Arithmetic, surface, volume and sauter mean diameter (µm). The sauter mean is the diameter of a drop having the same volume to surface area ratio as the total volume of all the drops to the total surface area of all the drops. These parameters are

calculated as follows, where d_i is the diameter of droplet i and n is the total number of droplets:

$$D_{10} = \frac{\sum_{i=1}^{n} d_i}{n} \quad (3) \qquad D_{20} = \sqrt{\frac{\sum_{i=1}^{n} d_i^2}{n}} \quad (4) \qquad D_{30} = \sqrt[3]{\frac{\sum_{i=1}^{n} d_i^3}{n}} \quad (5) \qquad D_{32} = \frac{\sum_{i=1}^{n} d_i^3}{\sum_{i=1}^{n} d_i^2} \quad (6)$$

- NMD: Number mean diameter, 50% of the number of drops is smaller than this value (µm).
- RSF: Relative Span Factor, a dimensionless parameter indicative of the uniformity of the drop size distribution defined as:

$$RSF = \frac{D_{v0.9} - D_{v0.1}}{VMD} \qquad (7)$$

- V_{vol50}: 50 percent of the total spray volume (or mass) is made up of droplets with velocities smaller than this value ($m.s^{-1}$).

Figure 6 presents the cumulative volumetric droplet size distribution for different types (ATR: hollow cone, API: standard flat fan, AXI: wide range flat fan, ADI: anti-drift flat fan, and AVI: air induction) and sizes of Albuz agricultural spray nozzles at a spray pressure of 3 bar. In figure 7, the volumetric droplet size distribution is presented cumulatively for different types and sizes of Hardi spray nozzles (F: standard flat fan, LD: pre-orifice flat fan, and Injet: air induction) In both cases, the droplet size distributions of five BCPC reference flat fan nozzles for nozzle classification are presented, i.e. Delavan LF 110 01 at 4.5 bar (Very fine/Fine), Lurmark F 110 03 at 3 bar (Fine/Medium), Lechler LU 120 06 at 2 bar (Medium/Coarse), TeeJet 80 08 at 2.5 bar (Coarse/Very Coarse) and TeeJet 80 15 at 2 bar (Very Coarse/Extremely Coarse). These reference nozzles are used to define the boundaries of the six spray categories: Very Fine (VF), Fine (F), Medium (M), Coarse (C), Very Coarse (VC) and Extremely Coarse (EC). This classification is based on the comparison of the droplet size spectrum ($D_{v0.1}$, VMD and $D_{v0.9}$) produced by a spray nozzle at a given pressure with these reference spectra (fig. 8). In figure 8, the 95% confidence intervals for the reference nozzles are indicated. Other nozzle-pressure combinations show similar repeatability.

Besides droplet size, droplet velocity is another important spray characteristic. In figure 9, the volumetric droplet velocity distribution for the same Hardi and reference nozzles as in figures 7 and 8 is presented cumulatively. Finally, in Table 3, an overview is given of different droplet characteristics of the 32 tested nozzle-pressure combinations.

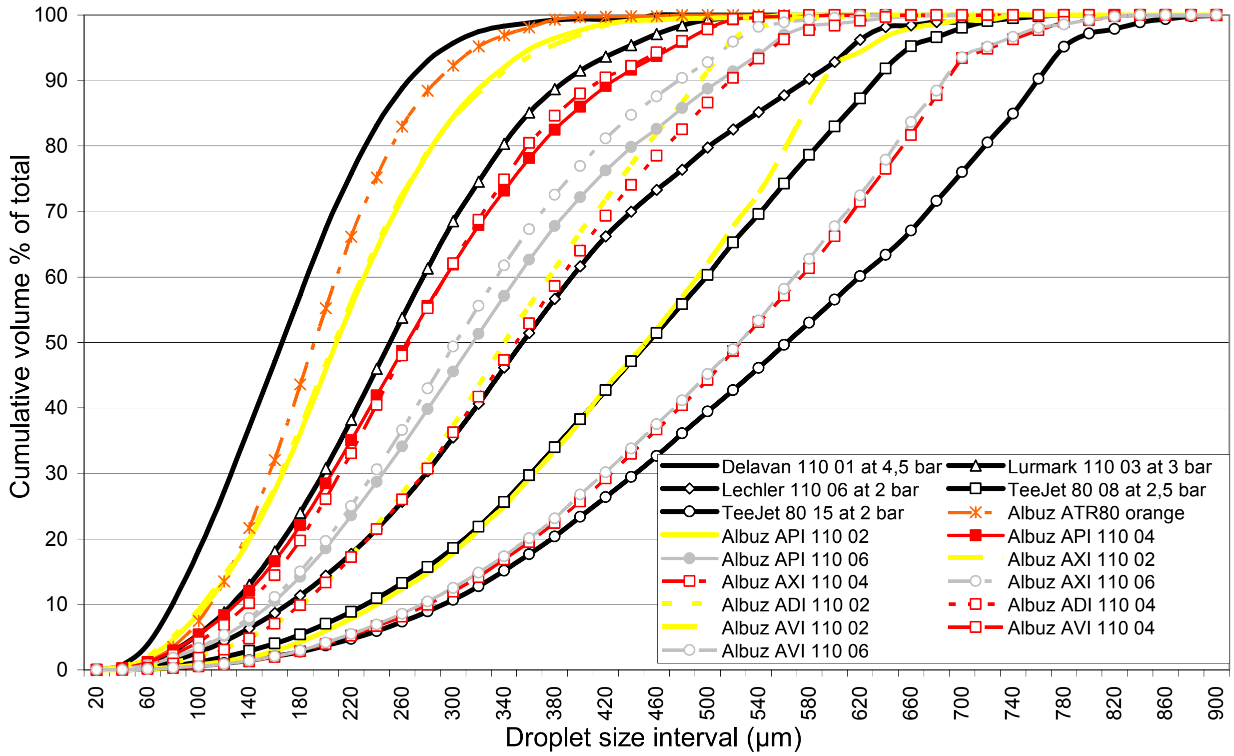

Figure 6. Cumulative volumetric droplet size distribution for different Albuz nozzles at a pressure of 3 bar and the 5 BCPC reference nozzles.

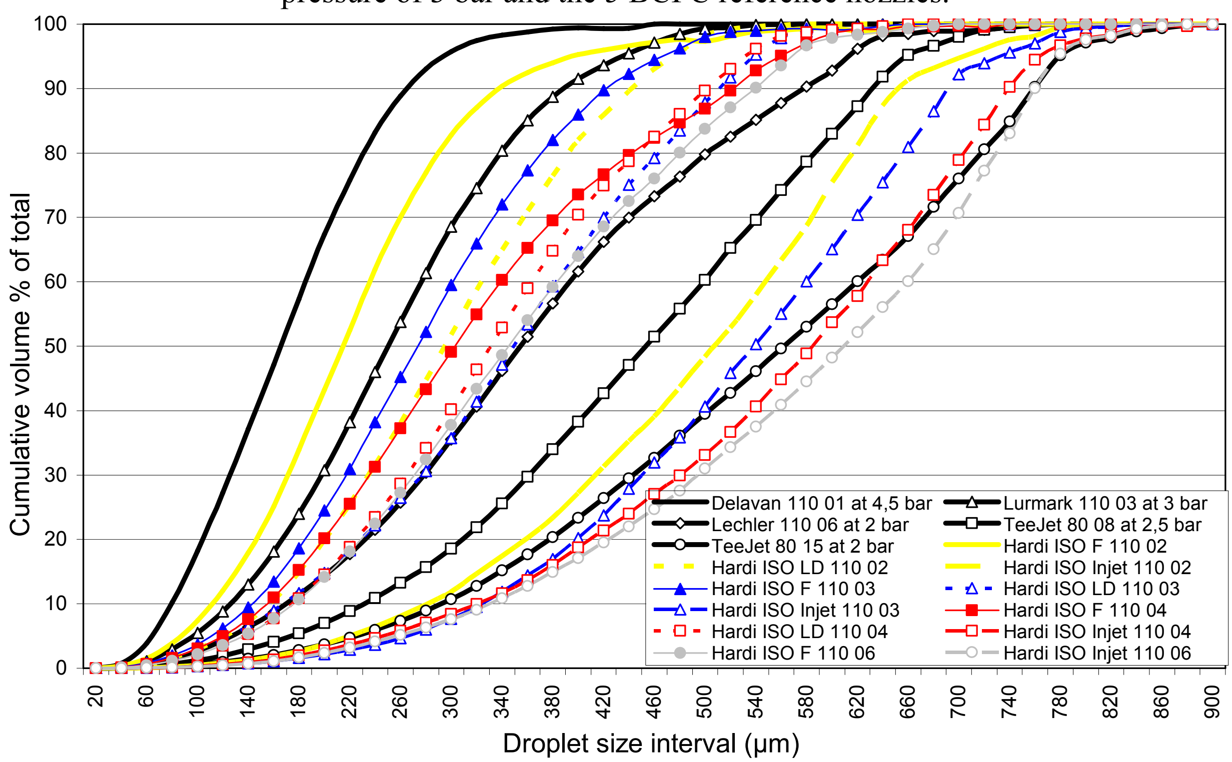

Figure 7. Cumulative volumetric droplet size distribution for different Hardi nozzles at a pressure of 3 bar and the 5 BCPC reference nozzles.

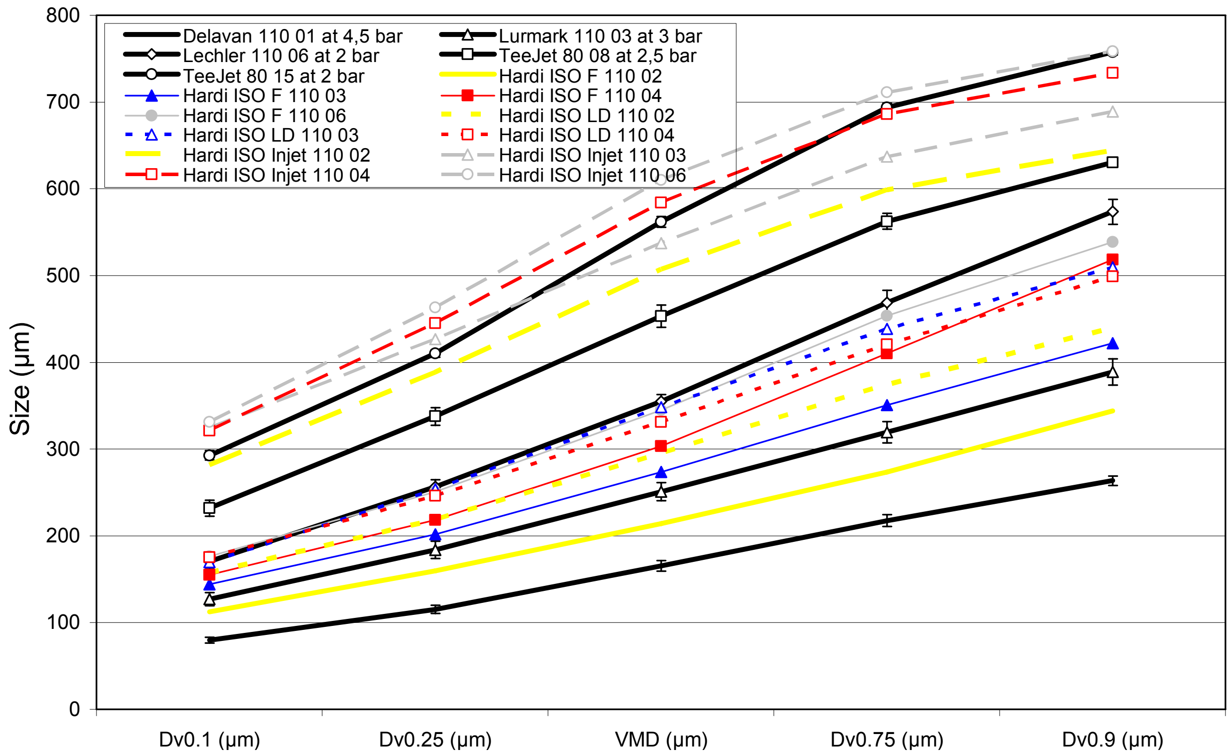

Figure 8. Droplet size characteristics $D_{v0.1}$, $D_{v0.25}$, VMD, $D_{v0.75}$ and $D_{v0.9}$ for different Hardi nozzles and the 5 BCPC reference nozzles.

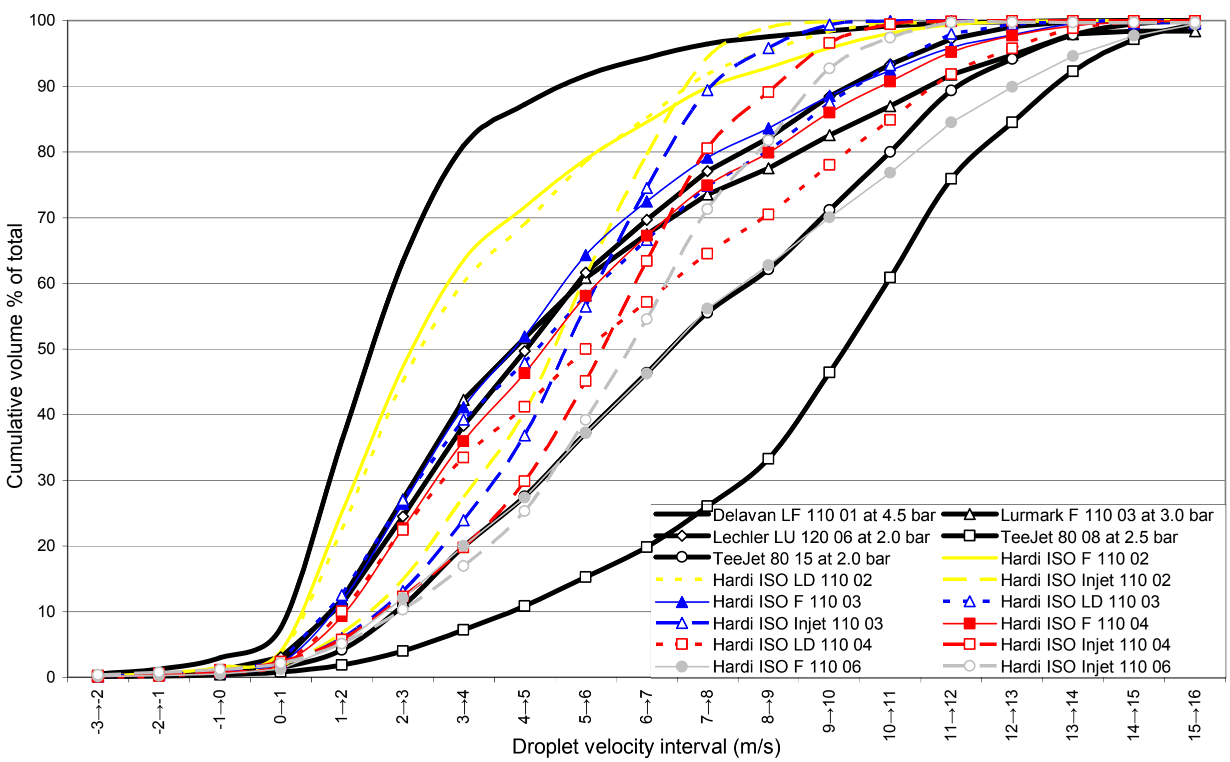

Figure 9. Cumulative volumetric droplet velocity distribution for different Hardi nozzles and the 5 BCPC reference nozzles.

Droplet sizes vary from a few micrometres up to some hundreds of micrometres depending on the nozzle type and size. For the same nozzle size and pressure, cone nozzles produce the finest droplet size spectrum followed by standard flat fan nozzles, low-drift flat fan nozzles and air induction nozzles (Table 3). For the same nozzle type and pressure, bigger ISO nozzle sizes produce a coarser spray compared to smaller ISO nozzle sizes. As expected, the 5 BCPC reference nozzles cover the entire range of measured droplet sizes (figs 7 & 8). Along with droplet size spectrum, each nozzle-pressure combination produces a droplet velocity spectrum with velocities varying from about 0 $m.s^{-1}$ up to 15 $m.s^{-1}$ (fig. 9). Moreover, there is a strong correlation between droplet sizes and velocities. In general, coarser sprays correspond with higher droplet velocities. For air induction nozzles, droplet velocities are smaller mainly because of the big pressure drop in the nozzle created by a combination of Venturi and pre-orifice effect. This is illustrated by the steeper curves for air induction nozzles in figure 9. The effect of the possible presence of small air bubbles in the droplets, which make them less heavy, is less important because only few air is included using water at a pressure of 3 bar (Combellack & Miller, 2001) .

4. CONCLUSION

As a basis for a research project about agricultural spray drift, a measuring set-up and protocol to measure droplets sizes and velocities generated by agricultural spray nozzles using a Phase Doppler Particle Analyser (PDPA) was developed. The PDPA is capable of producing lots of useful, informative and repeatable data. From the results, the importance of the nozzle type and size on the droplet size and velocity generated is clear. For the same nozzle size and spray pressure, cone nozzles produce the finest droplet size spectrum followed by standard flat fan nozzles, low-drift flat fan nozzles and air induction nozzles. The bigger the ISO nozzle size, the bigger the droplet size spectrum. Moreover, droplet size and droplet velocity spectra are correlated to each other. This information is very useful with regard to the risk of spray drift and the quantity and distribution of the deposit on the target. In future, results will be linked to the drift potential of different nozzle-pressure combinations and used as an input for a Computational Fluid Dynamics spray drift model.

5. ACKNOWLEDGEMENTS

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Table 3. Droplet characteristics (average ± standard deviation) of 32 nozzle-pressure

Nozzle type	Pressure (bar)	Nominal flow rate ($l.min^{-1}$)	BCPC*	$D_{v0.1}$ (µm)	VMD (µm)	$D_{v0.9}$ (µm)	V_{100} (%)	V_{200} (%)	D_{10} (µm)	D_{20} (µm)	D_{30} (µm)	D_{32} (µm)	NMD (µm)	RSF	V_{vol50} ($m.s^{-1}$)
Delavan 110 01	4.5	0.45	VF/F	79.7 ± 4.3	165.4 ± 8.0	263.5 ± 7.5	18.3 ± 2.4	67.4 ± 3.9	71.3 ± 3.8	85.2 ± 4.3	99.6 ± 4.4	136.3 ± 5.2	59.6 ± 3.3	1.1 ± 0.1	1.7 ± 0.2
Lurmark 110 03	3	1.18	F/M	127.2 ± 10.2	251.0 ± 14.0	389.1 ± 20.3	5.5 ± 1.2	30.8 ± 4.6	92.7 ± 5.7	117.5 ± 7.1	141.8 ± 8.3	206.7 ± 11.8	68.6 ± 3.5	1.0 ± 0.1	3.9 ± 0.5
Lechler 110 06	2	1.93	M/C	170.8 ± 10.7	355.0 ± 10.7	573.5 ± 19.5	2.7 ± 0.3	14.4 ± 1.9	108.6 ± 2.9	143.9 ± 4.8	180.7 ± 6.1	285.1 ± 10.4	74.7 ± 1.6	1.1 ± 0.1	4.4 ± 0.3
TeeJet 80 08	2.5	2.88	C/VC	231.8 ± 12.5	453.0 ± 17.2	630.5 ± 7.3	1.2 ± 0.2	7.0 ± 1.0	139.4 ± 5.9	187.8 ± 8.3	234.5 ± 9.7	365.4 ± 13.5	89.8 ± 2.8	0.9 ± 0.0	9.6 ± 0.2
TeeJet 80 15	2	4.9	VC/EC	292.7 ± 7.1	561.8 ± 8.3	757.4 ± 4.7	0.6 ± 0.1	3.7 ± 0.4	164.1 ± 7.5	227.1 ± 8.5	285.8 ± 8.4	452.7 ± 7.2	99.3 ± 5.9	0.8 ± 0.0	6.6 ± 0.3
Albuz ATR80 blue	3	1.94	M	150.1 ± 5.2	298.6 ± 14.0	474.4 ± 33.5	3.2 ± 0.7	21.0 ± 1.7	114.7 ± 18.1	142.7 ± 15.3	170.9 ± 11.6	246.4 ± 5.7	88.6 ± 23	1.1 ± 0.1	3.5 ± 0.2
Albuz ATR80 green	3	1.41	M	137.5 ± 9.4	256.2 ± 7.2	409.0 ± 12.2	3.9 ± 1.2	28.6 ± 2.2	113.2 ± 14.3	137.0 ± 13.4	160.0 ± 11.6	218.8 ± 6.9	92.1 ± 18.5	1.1 ± 0.0	2.6 ± 0.2
Albuz ATR80 orange	3	0.78	F	109.9 ± 7.0	191.1 ± 5.3	286.5 ± 9.1	7.5 ± 2.0	55.2 ± 3.0	97.7 ± 6.8	114.7 ± 6.9	130.1 ± 6.2	167.5 ± 4.8	85.1 ± 10.1	0.9 ± 0.1	1.2 ± 0.2
Albuz API 110 02	3	0.8	F	106.0 ± 4.9	208.3 ± 6.2	325.8 ± 8.4	8.7 ± 1.0	45.9 ± 3.2	81.4 ± 2.3	101.6 ± 3	121.5 ± 3.4	173.7 ± 5.1	62.3 ± 1.9	1.1 ± 0.0	2.1 ± 0.2
Albuz API 110 04	3	1.6	M	129.9 ± 5.9	263.6 ± 5.7	424.7 ± 13.1	5.4 ± 0.6	28.4 ± 1.7	85.7 ± 2.8	112.2 ± 3.5	139.2 ± 3.7	214.1 ± 5.1	61.2 ± 1.9	1.1 ± 0.1	3.5 ± 0.4
Albuz API 110 06	3	2.4	M	157.1 ± 6.6	315.4 ± 3.9	508.5 ± 18.4	3.3 ± 0.4	18.5 ± 1.3	97.0 ± 5.2	129.7 ± 6.1	162.6 ± 5.8	255.6 ± 4.3	66.2 ± 3.6	1.1 ± 0.1	4.8 ± 0.3
Albuz AXI 110 02	3	0.8	F	104.0 ± 4.1	207.0 ± 5.0	330.0 ± 6.2	9.2 ± 1.0	46.6 ± 2.4	77.2 ± 1.7	97.6 ± 2.2	117.8 ± 2.7	171.8 ± 4.7	58.5 ± 2.2	1.1 ± 0.0	1.6 ± 0.2
Albuz AXI 110 04	3	1.6	M	139.5 ± 6.5	265.5 ± 7.3	416.9 ± 16.5	4.2 ± 0.4	26.1 ± 2.3	97.9 ± 2.5	125.1 ± 3.1	151.4 ± 3.6	221.7 ± 6.1	70.7 ± 2.0	1.0 ± 0.1	3.5 ± 0.3
Albuz AXI 110 06	3	2.4	M	154.1 ± 10.6	302.2 ± 6.9	476.0 ± 7.1	3.3 ± 0.5	19.7 ± 2.4	99.8 ± 5.4	131.4 ± 6.9	162.4 ± 7.5	247.9 ± 8.9	69.0 ± 3.8	1.1 ± 0.0	5.1 ± 0.5
Albuz ADI 110 02	3	0.8	M	182.7 ± 16.4	341.7 ± 22.0	492.0 ± 9.7	2.1 ± 0.5	13.2 ± 2.8	110.1 ± 8.6	149.0 ± 12.1	184.4 ± 14.0	282.5 ± 18.9	70.3 ± 3.8	0.9 ± 0.1	2.7 ± 0.2
Albuz ADI 110 04	3	1.6	M	181.6 ± 15.4	351.1 ± 23.3	509.9 ± 41.2	1.8 ± 0.5	13.3 ± 3.0	119.3 ± 15.2	157.9 ± 17.2	193.2 ± 18.4	289.5 ± 21.3	83.5 ± 13.0	0.9 ± 0.1	3.0 ± 0.6
Albuz AVI 110 02	3	0.8	C	242.4 ± 19.9	450.4 ± 23.7	589.4 ± 10.7	0.7 ± 0.3	5.9 ± 1.6	158.8 ± 20.7	210.2 ± 23.2	254.3 ± 23.0	372.8 ± 20.3	111.1± 20.6	0.8 ± 0.1	4.5 ± 0.2
Albuz AVI 110 04	3	1.6	VC	280.3 ± 10.5	526.5 ± 9.1	684.8 ± 10.7	0.5 ± 0.1	3.9 ± 0.7	164.3 ± 12.2	227.1 ± 13.3	281.2 ± 12.6	431.3 ± 9.4	103.4± 11.3	0.8 ± 0.0	5.3 ± 0.2
Albuz AVI 110 06	3	2.4	VC	276.2 ± 9.9	524.8 ± 10.0	684.0 ± 7.0	0.5 ± 0.1	4.1 ± 0.5	159.7 ± 11.4	221.4 ± 12.5	275.3 ± 11.9	426.0 ± 7.6	98.7 ± 9.6	0.8 ± 0.0	5.5 ± 0.2
Hardi ISO F 110 02	3	0.8	F	112.5 ± 10.7	214.2 ± 7.9	343.9 ± 29.9	7.4 ± 1.8	43.2 ± 4.0	83.7 ± 6.9	105.4 ± 8.4	126.2 ± 9.1	181.1 ± 10.9	64.1 ± 5.6	1.1 ± 0.1	2.4 ± 0.3
Hardi ISO F110 03	4	1.39	F	117.5 ± 5.5	246.5 ± 6.7	426.0 ± 28.0	6.6 ± 0.9	33.5 ± 2.6	93.2 ± 3.2	115.2 ± 4.1	138.7 ± 4.5	201.2 ± 6.3	71.8 ± 2.6	1.3 ± 0.1	3.8 ± 0.8
Hardi ISO F 110 03	3	1.2	M	144.1 ± 8.9	273.6 ± 10.9	421.9 ± 21.3	3.7 ± 0.7	24.5 ± 2.9	96.0 ± 5.9	125.3 ± 6.8	152.9 ± 6.8	227.9 ± 8.2	67.9 ± 5.1	1.0 ± 0.1	3.9 ± 0.4
Hardi ISO F110 03	2	0.98	M	131.2 ± 16.5	265.4 ± 28.2	399.3 ± 17.8	5.3 ± 2.1	28.7 ± 8.5	97.1 ± 10.9	122.7 ± 13.4	148 ± 15.5	215.5 ± 21.2	72.8 ± 5.7	1.0 ± 0.1	3.3 ± 0.5
Hardi ISO F 110 04	3	1.6	M	154.9 ± 7.7	303.4 ± 10.3	518.3 ± 34.1	3.0 ± 0.4	20.1 ± 1.8	98.7 ± 2.6	131.2 ± 4.0	163.1 ± 5.3	252.1 ± 9.9	67.7 ± 2.1	1.2 ± 0.1	4.6 ± 0.2
Hardi ISO F 110 06	3	2.4	M	176.1 ± 7.3	345.1 ± 5.5	538.7 ± 10.9	2.2 ± 0.3	14.2 ± 1.4	107.1 ± 3.2	144.9 ± 4.5	181.2 ± 5.1	283.3 ± 6.9	70.8 ± 2.6	1.1 ± 0.0	6.6 ± 0.2
Hardi ISO LD 110 02	3	0.8	M	157.4 ± 7.6	294.9 ± 9.7	440.0 ± 16.2	2.9 ± 0.4	19.9 ± 2.3	107.8 ± 4.6	139.0 ± 5.7	168.1 ± 6.0	245.8 ± 7.8	76.2 ± 3.0	1.0 ± 0.1	2.6 ± 0.1
Hardi ISO LD 110 03	3	1.2	M	169.8 ± 18.9	348.2 ± 14.1	509.3 ± 8.4	2.7 ± 0.8	14.8 ± 3.2	116.7 ± 10.5	150.8 ± 13.9	185.1 ± 15.2	279.0 ± 17.4	82.5 ± 5.4	1.0 ± 0.1	4.4 ± 0.4
Hardi ISO LD 110 04	3	1.6	M	175.1 ± 3.7	331.2 ± 6.4	499.2 ± 11.9	2.1 ± 0.2	14.5 ± 0.9	117.3 ± 3.0	152.9 ± 3.6	186.1 ± 4.1	275.9 ± 5.7	81.7 ± 3.3	1.0 ± 0.0	5.2 ± 0.4
Hardi ISO Injet 110 02	3	0.8	VC	281.6 ± 16	506.8 ± 27	644.7 ± 34.2	0.5 ± 0.1	3.7 ± 0.5	181.1 ± 13.8	240.3 ± 13.8	290.0 ± 13.9	422.7 ± 20.4	122.1± 17.9	0.7 ± 0.0	4.6 ± 0.0
Hardi ISO Injet 110 03	3	1.2	VC	324.3 ± 11.2	537.4 ± 16.9	689.1 ± 8.2	0.3 ± 0.1	2.2 ± 0.5	216.2 ± 23.2	281.2 ± 22	332.3 ± 19.6	464.8 ± 12.4	152.6 ± 35.4	0.7 ± 0.0	4.8 ± 0.1
Hardi ISO Injet 110 04	3	1.6	EC	321.3 ± 18.6	584.0 ± 23.2	733.5 ± 16.6	0.3 ± 0.1	2.8 ± 0.6	198.4 ± 14.5	267.0 ± 17.8	325.0 ± 18.7	481.4 ± 19.7	134.4 ± 13.8	0.7 ± 0.0	5.6 ± 0.1
Hardi ISO Injet 110 06	3	2.4	EC	331.2 ± 12.6	610.0 ± 21.2	758.3 ± 15.7	0.3 ± 0.1	2.3 ± 0.4	209.2 ± 13.3	280.5 ± 15.1	340.0 ± 15.5	499.5 ± 16.3	146.0 ± 17.0	0.7 ± 0.0	5.9 ± 0.3

* BCPC nozzle classification: VF = Very Fine; F = Fine; M = Medium; C = Coarse; VC = Very Coarse; XC = Extremely Coarse

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