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Spray nozzle characterization using a backlighted high speed imaging technique

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Summary

Agricultural pesticide sprays are applied with different types of spray nozzles each with its own spray characteristics. The objective of this study was to measure the macro-spray characteristics (spray angle, liquid sheet length, spray shape) from different types of hydraulic spray nozzles using a developed backlighted image acquisition system and image processing technique. Tests included five different nozzles (Albuz ATR orange and red, TeeJet XR 110 01, XR 110 04 and Al 110 04).

The results were compared and related well with the results from existing measuring techniques like a flow rate test bench, a spray distribution bench (horizontal patternator) and a Phase Doppler Particle Analyzer (PDPA) laser.

Key words: Spray characterization, spray angle, spray shape, high speed imaging

Introduction

The agricultural spray appliances (such as hydraulic nozzles) used for pesticide applications do not atomize the liquid into droplets of identical size and velocity but into a range of droplets of various sizes and velocities (Lefebvre, 1989). It is important to quantify and control these distributions because they influence the droplet trajectories and interactions with the target (Butler Ellis *et al*., 1997). Other important spray characteristics influencing the efficacy of the pesticide application process are, among others, the spray angle and spray shape, the volume distribution pattern and the liquid sheet length as the objective of spraying plant protection products (PPP) is to deliver an effective, uniform pesticide dose to the target area.

However, mechanisms of droplets leaving a nozzle and impacting the leaves are complex and difficult to quantify or model, while existing non-imaging measuring techniques are not able fully to characterize the spraying process. Therefore it is necessary to further improve the efficiency of pesticide spray applications. Without accurate quantification techniques, it is not possible to evaluate the characteristics of the processes in question.

The limitations of the non-imaging techniques (e.g. spray patternator) and the improvements in digital image acquisition and processing increased the interest in using high speed (HS) imaging techniques for spray characterization (Hijazi *et al*., 2012).

This paper has the objective to measure the macro spray characteristics from different types of hydraulic spray nozzles using the HS image acquisition system and image processing described by Vulgarakis *et al*. (2012). The results are compared with the existing non-imaging measuring techniques (if available) like spray distribution bench (horizontal patternator) and PDPA laser (Nuyttens *et al*., 2007). In a next step of this research, micro-spray characteristics (droplet size, velocity, direction) will be evaluated using a similar methodology.

Materials and Methods

A high speed (HS) image acquisition system (Vulgarakis *et al*., 2012) was used to measure the macro-spray characteristics (spray angle, spray shape and liquid sheet length) of five single hydraulic spray nozzles. The results of these measurements were compared with the results from the existing non-imaging measuring techniques (flow rate test bench, horizontal patternator).

Hydraulic spray nozzles

The spray characteristics of five different static spray nozzles were measured to evaluate the effect of nozzle type (hollow cone, standard flat fan and air inclusion flat fan nozzle), nozzle size (ISO 01 & 04) and spray angle (80° & 110°). Their properties are given in Table 1.

Table 1. *Properties of the tested hydraulic spray nozzles*

Nozzle type	Nozzle	Pressure (kPa)	Spray angle (°)	Nominal flow rate (L min^{-1})	Actual flow rate (L min^{-1})
Hollow cone	Albuz[a] ATR orange	600	80	1.08	1.104 ± 0.005
Hollow cone	Albuz[a] ATR red	800	80	1.73	1.740 ± 0.003
Standard flat fan	TeeJet[b] XR 110 01	400	110	0.45	0.443 ± 0.001
Standard flat fan	TeeJet[b] XR 110 04	400	110	1.82	1.829 ± 0.001
Air inclusion flat fan	TeeJet[b] AI 110 04	400	110	1.82	1.836 ± 0.000

[a]Saint – Gobain Solcera, Evreux Cedex, France; [b]TeeJet Technologies, Wheaton, USA.

Hollow cone nozzles generally provide the smallest droplet size distribution. Their spray pattern consists of droplets concentrated on the outer surface of a conically shaped volume. Furthermore, this is the most popular nozzle type for orchard and vineyard spray applications. An Albuz ATR orange (6.0 bar) and red (8.0 bar) hollow cone nozzle with 80° spray angles were tested. Besides, Dekeyser *et al*. (2013) used the same nozzle-pressure combinations for orchard spray applications.

Standard flat fan nozzles are the most commonly used nozzle type for horizontal boom sprayers. They produce a flat sheet of liquid resulting in a bell shaped spray distribution, comparable to a Gaussian distribution (Huyghebaert *et al*., 2001). A TeeJet XR 110 01 and XR 110 04, both at 4.0 bar with a 110°spray angle, were tested. The ISO 04 nozzle size is very commonly used in Western Europe. The small ISO 01 nozzle size was selected because of its fine, droplet size characteristics.

Air inclusion flat fan nozzles have two air inlets from which air is induced into the nozzle, mixing with spray liquid. As a result, the emitted spray contains large droplets, potentially with air bubbles, which reduce the risk of a droplet bouncing off a leaf surface. Therefore, air inclusion nozzles are the most popular drift reducing application technique. A TeeJet AI 110 04 nozzle was selected at 4.0 bar and with a 110° spray angle (Table 1).

The actual flow rate of all nozzle-pressure combinations was measured in ILVO's Spray Tech Lab (2013) (Fig 5a).

Image acquisition system for spray characterization

Two different high speed image acquisition systems were developed for micro and macro-spray characterization by Vulgarakis *et al*. (2012). Fig. 1 shows a schematic overview of the spray characterization system.

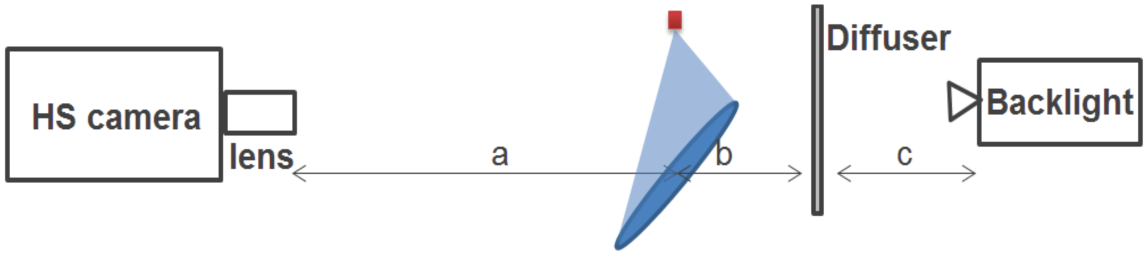

Fig.1. Image acquisition system for spray characterization (Vulgarakis *et al*., 2012).

The macro spray characteristics including the spray angle, shape and liquid sheet length have been investigated by an image acquisition system consisting of three main parts: a 500 W spotlight with a diffuser, a HS camera IDT N3 (8-bit dynamic range, 1280 × 1024 pixels) and a Macro Video Zoom Lens (Optem, 18-108, F/2.5, 20 mm focal length). The ground glass diffuser (TECHSPEC, Edmund Optics, USA) was used to reduce the light inhomogeneity and was placed between the background light and the lens (Fig. 1) (Lad *et al*., 2011).The distance between the camera and nozzle was 14.3 cm resulting in a field of view (FOV) of 110 mm × 88 mm with a pixel resolution of 85.8 µm. Images are acquired at a grabbing rate of 1000 fps with an exposure time of 15 µs and + 3dB sensor gain (Massinon & Lebeau, 2012). The captured images have 1280 × 1024 pixels with 8 bits of grey scale resolution. The Motion Studio software (IDT, Lommel, Belgium, version: 2.09, 2011) was used to view and save the images. The specifications of the system are shown in Table 2.

Table 2. *Spray characterization system specifications (Vulgarakis* et al.*, 2012)*

HS camera	IDT N3 (8-bit dynamic range, 1280 × 1024 pixels), 1000 fps
Exposure time	15 µs
Lens	Macro Video Zoom Lens (Optem, 18-108, F/2.5, 20 mm focal length)
Backlight	500 W Spotlight
Diffuser	220 ground glass diffuser
Distances a/b/c	430 mm / 80 mm / 240 mm
FOV	88.0 mm × 110 mm
Pixel resolution	85.8 µm

Image analysis for spray characterization

Macro-spray characteristics were determined by image analysis using dedicated algorithms developed in Matlab® (The MathWorks Company, Massachusetts, USA). The key of automatically measuring the spray angle is to find the edge of the most left side and the most right side of the spray (Zhang *et al*., 2011). The algorithm for spray angle image analysis consisted of different steps: 1. acquiring the spray images (Fig. 2a), 2. noise reduction and image enhancement (Fig. 2b), 3. image binarization (Fig. 2c), 4. applying morphological operations and spray edge detection (Fig. 2d,e) and 5. detection of the two boundary lines of the spray angle with their orientation (Fig. 2f). Detection of the boundary lines was the key problem for spray angle determination, so choosing the appropriate morphological operators was crucial for the detection accuracy.

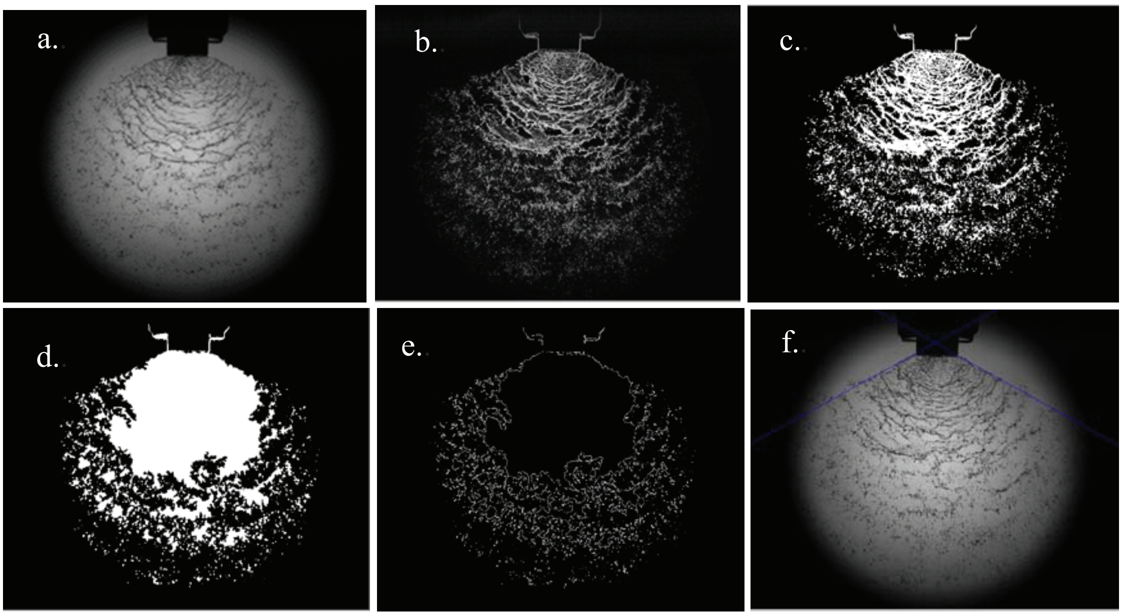

Fig. 2. Steps in the spray angle image analysis illustrated for the TeeJet XR 110 04.

The spray liquid sheet length is based on finding the biggest object and its length (starting from the nozzle exit – Fig. 2d, 3a). For this purpose the hollow cone nozzles, with their conical spray pattern, were put at an angle of 40° towards the diffuser and a region of interest (ROI) was selected beneath the nozzle. In this way only the part of spray which is sharp in the FOV is selected and used for the liquid sheet determination (Fig. 3b, c).

Spray shape analysis was done by moving every single nozzle using a 3D positioning table (Nuyttens *et al*., 2007) in horizontal steps of 2.5 cm to both sides and in vertical steps of 5 cm in order to scan the spray fan. In this manner 140 images with flat fan nozzles and 68 images with hollow cone nozzles of the spray were needed to be taken and connected to view the whole spray up to 20 cm beneath the nozzle. The spray shape was achieved by edge detection (Fig. 4). All measurements were done with tap water and repeated five times.

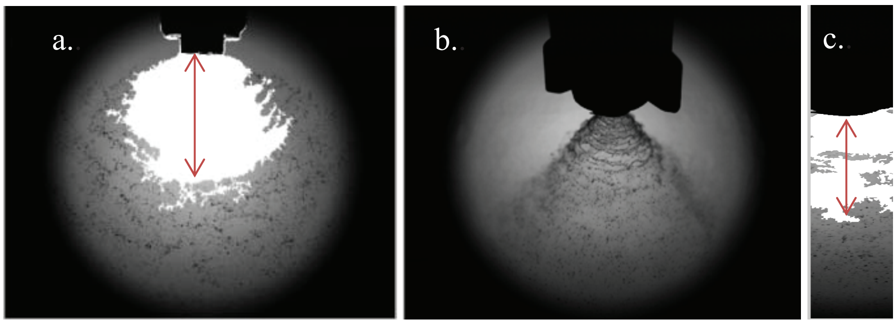

Fig. 3 Spray liquid sheet image analysis for (a) the TeeJet XR 11004 nozzle and (b) and (c) the Albuz ATR red nozzle.

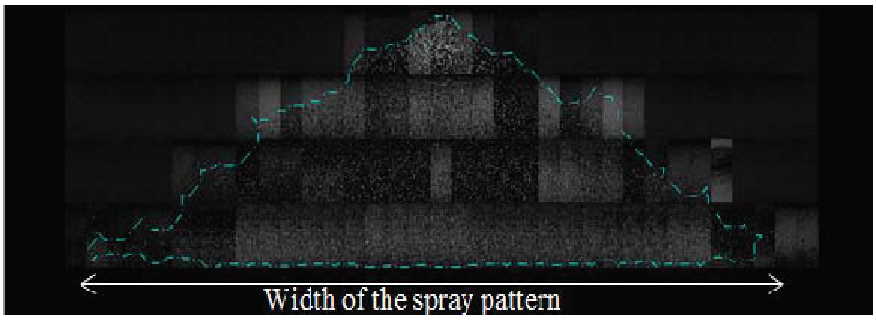

Fig. 4. Spray shape analysis of the TeeJet XR110 04 up to 20 cm below the nozzle.

Existing non-imaging techniques for spray characterization

A wide variety of non-imaging measurement techniques have been used to determine the spray nozzle characteristics. Spray distribution measurements are mainly carried out using intrusive methods like a patternator or spray scanner. In this work, a horizontal patternator (AAMS, Maldegem, Belgium, Fig. 5b,c) was used to measure the cross flow distribution of the five nozzle-pressure combinations according to the International Standard ISO 5692/1 (1996) in the ILVO Spray Tech Lab (2013). Water at a constant pressure (± 0.1 bar) was sprayed from one static nozzle on to a 3.0 m wide channeled table and collected in a sloping section with 0.05 m wide groves which drain into calibrated collecting tubes. All nozzle-pressure combinations were tested at three different heights, i.e. 15, 30 and 50 cm, and in four repetitions. Nozzles were turned 180° (front/behind) between every repetition. The flat fan nozzles were installed with the longest axis of the fan perpendicular to the measuring grooves. For every nozzle setting the spray volumes in every tube, the collecting time, the relative humidity and the ambient and water temperature were registered and saved. Each measurement was stopped as soon as the amount of liquid collected in one of the tubes reached 90% of its capacity.

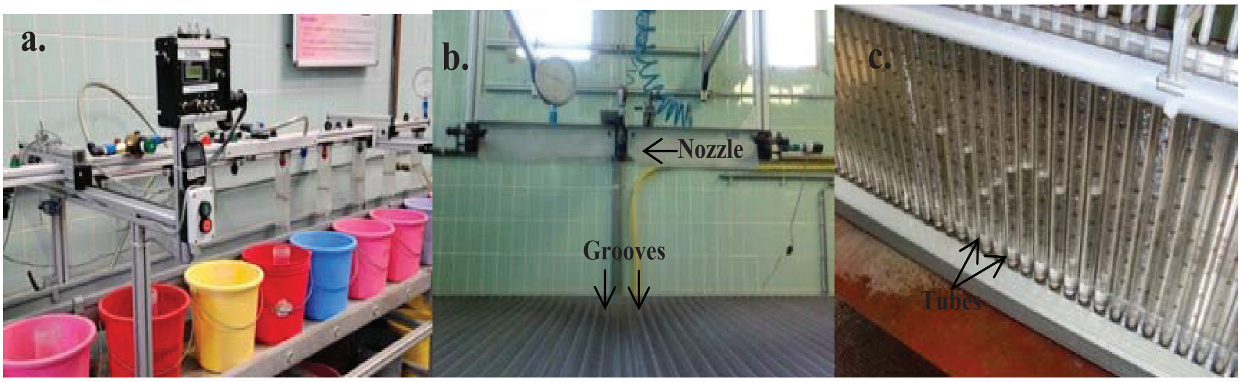

Fig. 5. Non-imaging techniques for spray characterization at ILVO's Spray Tech Lab: (a) flow rate test bench and (b) & (c) horizontal patternator.

The spray angle and spray shape of a single nozzle depend on the nozzle height, type and pressure and the angle at which the nozzle is oriented (Azimi *et al*., 1985). The actual spray angle (θ) for every nozzle measurement with the horizontal patternator was trigonometrically calculated based on the nozzle height and spray pattern width defined as the distance between the centers of the last filled tubes with at least 20 mL (Fig. 6). As it is not possible to know exactly where the spray pattern finishes (± 2.5 cm), this measuring error is brought into account while calculating the measuring accuracy on the actual spray angle (Table 3). The spray shape was estimated based on the width of the spray pattern at the three different heights and the position of the nozzle.

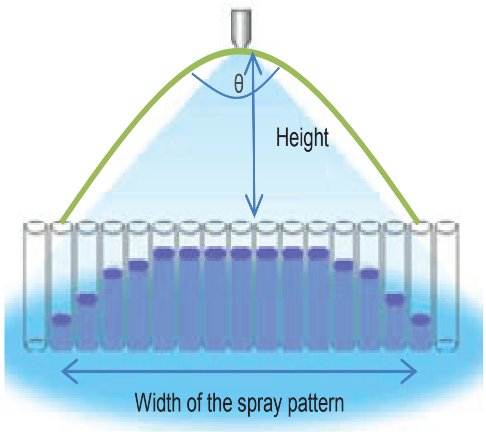

Fig. 6. Spray angle (θ) estimation based on cross flow distribution measurement and spray height.

Results and Discussion

Spray angle

The spray angles of the different nozzle-pressure combinations at three different heights (15, 30 and 50 cm) achieved with the horizontal patternator and with the imaging technique at the nozzle orifice (0 cm) are given in Table 3. In general the measured spray angles were higher than the nominal spray angles except for the Albuz red nozzle at 30 cm and the TeeJet XR 110 01 at the nozzle exit. Moreover, based on the results at 15, 30 and 50 cm, actual spray angle decreases with an increase of nozzle height because of the effect of gravity. This effect is most pronounced for the finer sprays. For the hollow cone and the air inclusion nozzle, the imaging technique gives a good representation of the spray angle while the spray angle is underestimated for both standard flat fan nozzles.

Liquid sheet length

The smallest liquid sheet length was calculated for TeeJet XR 110 01 nozzle (18.5 mm), followed by the two hollow cone nozzles (27.4 & 31.3 mm). The longest liquid sheets were found for the TeeJet XR 110 04 (38.9 mm) and TeeJet AI 110 04 nozzle (43.1 mm) (Table 3). Jasikova *et al.* (2011) measured a liquid sheet length for a full cone nozzle of 30 mm using imaging techniques.

Table 3. *Spray angles and liquid sheet lengths of the five nozzles-pressure combinations*

Nozzle type	Nozzle	Pressure (kPa)	Nozzle height	Nominal spray angle	Actual spray angle (°)	Liquid sheet length (mm)
Hollow cone	Albuz ATR orange	600	0 cm	80°	96.9 ± 6.7	27.4 ± 1.1
			15 cm		98.8 ± 7.2	
			30 cm		94.5 ± 3.6	
			50 cm		80.7 ± 2.7	
Hollow cone	Albuz ATR red	800	0 cm	80°	86.6 ± 2.0	31.3 ± 3.1
			15 cm		98.8 ± 7.2	
			30 cm		84.9 ± 4.2	
			50 cm		80.7 ± 2.7	
Standard flat fan	TeeJet XR 110 01	400	0 cm	110°	108.5 ± 1.3	18.5 ± 1.8
			15 cm		124.8 ± 2.0	
			30 cm		124.8 ± 2.0	
			50 cm		110.8 ± 1.5	
Standard flat fan	TeeJet XR 110 04	400	0 cm	110°	113.8 ± 3.4	38.9 ± 1.8
			15 cm		130.3 ± 2.8	
			30 cm		128.9 ± 1.5	
			50 cm		119.0 ± 1.2	
Air inclusion flat fan	TeeJet AI 110 04	400	0 cm	110°	120.1 ± 8.7	43.1 ± 2.0
			15 cm		124.8 ± 2.0	
			30 cm		124.8 ± 2.0	
			50 cm		117.5 ± 1.3	

Spray shape

Fig. 7 presents the results of the cross flow distribution measurements expressed in relative values (% of the total volume).of the TeeJet XR 110 04 at 15, 30 and 50 cm. Further, Fig. 8 presents the average spray shape of the TeeJet XR 110 04 with the imaging system based on five replicates. Hence from the spray shape, we calculated the spray pattern width of all selected nozzles (Table 1) at four different heights (5, 10, 15 and 20 cm) and the corresponding spray angles and compared them with the patternator results at 15 cm height (Table 4).

From the spray distribution measurements, it is clear that nozzle height has an important effect on the spray distribution. Greater nozzle to target distance allows the spray droplets to spread more and to create a wider individual spray pattern. In general, the highest spray volume was found directly under the nozzle and decreases on both sides of the nozzle. The higher the nozzle, the smoother are the spray distribution peaks compared to those produced at 15 cm nozzle height. Because of the effect of gravity, the spray shape was parabolic and the spray angle generally decreases with increased nozzle height.

Table 4. *Spray pattern width at four heights (image analysis) and at 15 cm (patternator) for the nozzle-pressure combinations*

		Imaging system		Horizontal patternator		Relative error (%)
Nozzle type	Nozzle height (cm)	Spray pattern width (cm)	Actual spray angle (°)	Spray pattern width (cm)	Actual spray angle (°)	Actual spray angle
Hollow cone	5	12.3	101.6	-	-	-
	10	27.0	103.9	-	-	-
	15	36.8	101.6	35	98.8 ± 7.2	2.8
	20	41.7	92.4	-	-	-
Hollow cone	5	12.3	101.6	-	-	-
	10	22.1	95.7	-	-	-
	15	31.9	93.5	35	98.8 ± 7.2	5.4
	20	41.7	92.4	-	-	-
Standard flat fan	5	22.1	131.3	-	-	-
	10	41.7	128.8	-	-	-
	15	56.4	124.0	55	124.8 ± 2.0	0.6
	20	76.1	124.5	-	-	-
Standard flat fan	5	22.1	131.3	-	-	-
	10	46.6	133.9	-	-	-
	15	63.8	129.6	65	130.3 ± 2.8	0.5
	20	85.9	130.0	-	-	-
Air inclusion flat fan	5	22.1	131.3	-	-	-
	10	41.7	128.8	-	-	-
	15	56.4	124.0	55	124.8 ± 2.0	0.6
	20	76.1	124.5	-	-	-

Table 4 shows the comparison of image analysis results and horizontal patternator results. From this table, the spray angle relative error for TeeJet XR 110 04 at 15 cm height was 0.5% while for TeeJet XR 110 01 and AI 110 04, 0.6%. The spray angle relative error was bigger for the hollow cone Albuz ATR orange and red nozzles: 2.8% and 5.4% respectively.

Accordingly, the low spray angle relative error meets well the demands for using this technique. In closing, similar results for the spray shape, pattern width and spray angle were found using the horizontal patternator and the imaging technique.

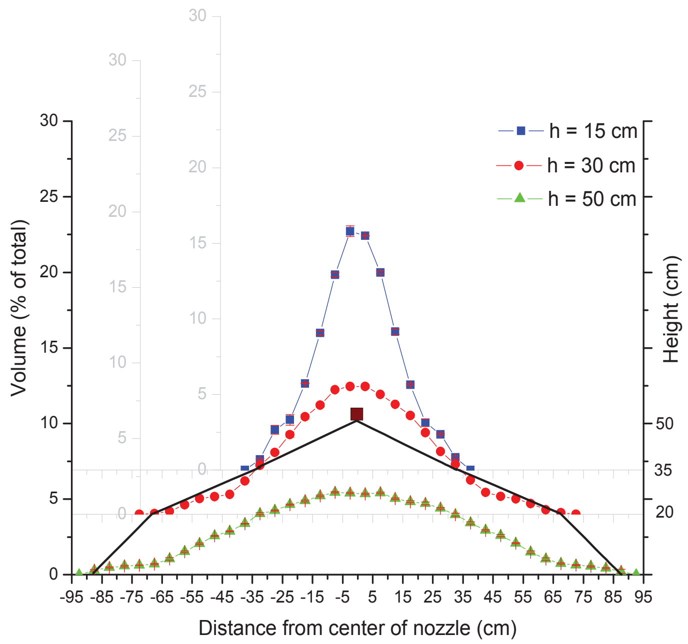

Fig. 7. Spray distribution measurements (% and SD) at three different heights of the TeeJet XR 110 04 at 4.0 bar and the resulting estimated spray shape.

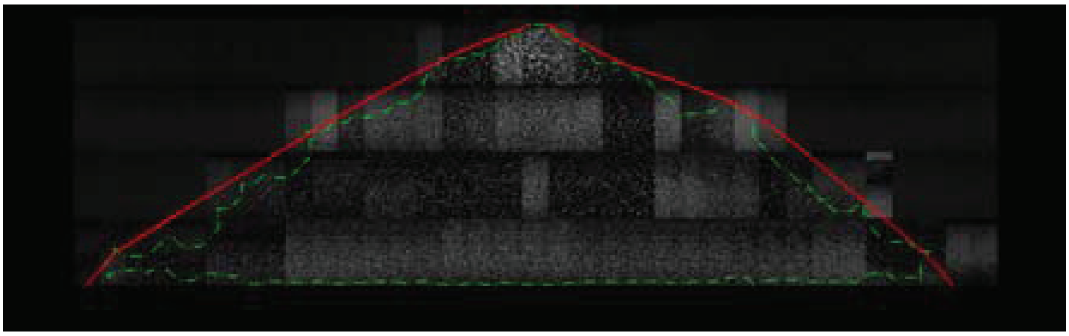

Fig. 8. Spray shape estimation for TeeJet XR 110 04 nozzle at 4.0 bar up to 20 cm below the nozzle.

Conclusions

A HS image acquisition set-up and image processing algorithms were developed to evaluate the macro-spray characteristics, i.e. spray angle, spray shape and liquid sheet length, of five different spray nozzles using image acquisition and processing. The imaging system consisted of a HS camera, a Macro Video Zoom Lens, a diffuser and a backlight spotlight. Results were compared with the results from traditional non-imaging techniques. The results from the imaging technique have shown that it is possible to measure the spray characteristics in a nonintrusive and correct way using a correct image acquisition setup and image processing algorithm. Future research will focus on the determination of the micro-spray characteristics using HS imaging techniques such as the droplet sizes, droplet velocities and directions and the structure of the individual droplets using a Xenon light source, a microscopic lens and a HS camera.

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