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Performance of Selected Agricultural Spray Nozzles using Particle Image Velocimetry

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ABSTRACT

The aim of the present study was to investigate the influence of nozzle configurations on spray drift and explain the influences using several atomization characteristics (length of spray sheet, spray angle, velocity distribution of flow field, fluctuation of velocity, and droplet size). Nozzles manufactured by one company (Lechler GmbH, Germany) were tested by spraying local tap water in a wind tunnel at an operating pressure of 0.3 MPa and under room temperature. The nozzles tested were compact air-induction flat fan nozzles (IDK120-02, IDK120-03), standard flat fan nozzles (ST110-02, ST110-03), and hollow-cone swirl nozzles (TR80-02, TR80-03). The atomization process was recorded using a Particle Image Velocimetry (PIV) system, droplet size was measured by a Sympatec Helos laser-diffraction particle-size analyzer, and spray drift was evaluated in a wind tunnel with deposition measured using a calibrated fluorometer (Turner-Sequoia model 450). Results showed that spray drift was significantly different among nozzle types ($P<0.0005$) and that nozzle configurations influenced breakup length, spray angle, droplet size, and velocity. Nozzles producing larger droplet sizes had lower velocity. Smaller droplets were produced when longer and wider spray sheets were produced. Compared to ST and TR nozzles, IDK nozzles started to breakup in the center of the liquid sheet, producing droplets with larger diameter, lower velocity, and less velocity fluctuation. The IDK nozzle is a good choice for low spray drift at higher wind speeds.

Keywords: Atomization, Droplet size, Droplet velocity, Particle Image Velocimetry.

INTRODUCTION

Pesticide application is still the most effective and frequently used method to protect arable crops and fruit trees against diseases and insects in agriculture (Maynagh *et al*., 2009). To maximize the benefits of pesticides and minimize its environmental and public health risk, researchers are engaged in increasing the deposition of pesticide onto the target and decreasing the drift of pesticide away from the target zone during the application process (Hewitt, 1997). The initial size and velocity of droplets exiting from spray nozzles are the two main parameters that can influence the spray drift of pesticides (Reichard *et al*., 1992). The process of separating a liquid up into many small droplets is called atomization. This atomization process is influenced by the nozzle design, configuration (Czaczyk, 2012; Vallet and Tinet, 2013; Fritz *et al*., 2014), and by the physical properties of the sprayed liquid (Butler Ellis *et al*., 1997; Miller and Butler Ellis, 2000). Therefore, the nozzle configuration can influence pesticide drift via the droplet size and velocity.

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Many techniques have been used to study droplet size and/or velocity of agricultural spray nozzles. A widely used method is PDA (also known as Particle Dynamics Analysis or PDPA (Phase Doppler Particle Analyzer)) based on light-scattering interferometry. Many researchers, such as Nuyttens *et al*. (2007), Song *et al*. (2011), and Vallet and Tinet (2013) have used this technique to investigate spray characteristics and have found that droplet size was correlated to nozzle configuration and spray pressure. The PDA technique measures both size and velocity of individual droplets, but the measurement point has to be moved during the test to map the entire flow field.

Compared with PDA, imaging methods are capable of measuring the spray sheet over the entire field of view (FOV) of the camera rather than a single point. These methods are based on freezing particle motion in captured images. Imaging methods can be used to show that, for example, the spray discharged from a nozzle becomes unstable, perforated, and/or wavy and breaks up into filaments which then further break up into droplets (Lefebvre, 1989).

Different imaging test systems were developed according to their corresponding image processing algorithms used to measure spray characteristics. For example: (a) High-Speed Imaging system imaging atomization by Thompson and Rothstein (2007); (b) Particle/Droplet Image Analysis (PDIA) system recording part of spray and measuring size and velocity of single droplet by Kashdan *et al*. (2004, 2007); (c) Digital Image Analysis (DIA) system developed by Lad *et al*. (2011) to test droplet size, and (d) Particle Image Velocimetry (PIV) system used by Dorr *et al*. (2013) and Fritz *et al*. (2014) to study atomization and velocity field.

Different from most of the references mentioned above whose emphasis are on the droplet size distribution, this study explains the effect of the nozzle configuration (reflected as nozzle type) on the drift using velocity and fluctuation field of the entire spray. PIV was, therefore, employed in this study, whereas other techniques measure the velocity at a point or the velocity of every particle (Hijazi *et al*., 2012). The initial groundwork for a PIV theory was laid down by Adrian (1988), in which the expectation value of the auto-correlation function for a double-exposure continuous PIV image was described. Illuminated by a light source, the motion of a liquid sheet and droplets were made visible by using the droplets as tracers. From the positions of these tracer droplets at two instances of time, i.e. the droplet displacement, it is possible to infer the flow velocity field, as well as calculate the fluctuation distribution of velocity (Westerweel, 1997).

The object of this study was to investigate the influence of nozzle configurations on the drift of pesticide. Parameters such as length of spray sheet, spray angle, droplet size, velocity distribution, and velocity fluctuation were adopted to explain the influences.

MATERIALS AND METHODS

In this study, the complete atomization region was imaged and the velocity distribution in the atomization region was measured by a newer time-resolved PIV system (Dantec Dynamics A/S, Denmark) which has dual power lasers and can acquire high resolution PIV images at frame rates up to 16,000 fps with full camera resolution, while the system Dorr *et al*. (2013) used was a single-laser imaging system. Droplet size at a distance 250 mm away from each nozzle was also tested using a Sympatec Helos laser-diffraction particle-size analyzer (Sympatec GmbH, Germany). Six nozzles types commonly used to protect cotton against pest in China were selected for this study.

Spray Nozzles and Solution

Nozzle configuration was the independent parameter considered in this work and nozzles were selected to produce a range of droplet sizes and velocity distributions. Since the results of Butler Ellis *et al*. (2002) and Miller *et al*. (2008) showed considerable differences between droplet size and velocity distributions between different versions of the same nozzle design, all nozzles tested were manufactured by one company (Lechler GmbH in Germany). Nozzles test included: compact air-induction flat fan nozzles (IDK120-02, IDK120-03), standard flat fan nozzles (ST110-02, ST110-03), and hollow-cone swirl nozzles (TR80-02, TR80-03). The values 120, 110, and 80 in the labels were their nominal spray angles: 120°, 110°, and 80°, respectively. According to the standard used by Herbst (2001), three nozzles of each type were selected for measurement from 15 nozzles with a flow rate near the nominal value. Their flow rates were 0.79 (±0.01), 0.77 (±0.01), 0.77 (±0.02), 1.19 (±0.02), 1.19 (±0.03) and 1.18 (±0.01) L min^{-1} for IDK120-02, ST110-02, TR80-02, IDK120-03, ST110-03, and TR80-03 nozzles, respectively. The respective nominal flow rates of 02 nozzles and 03 nozzles were 0.78 and 1.17 L min^{-1}.

All experiments were conducted by spraying local tap water at the same operating pressure of 0.3 MPa and under room temperature. During testing, temperature of spray liquid was 31.5°C. The density, surface tension, and viscosity of the spray liquid was 1,000 kg m^{-3} 0.0716 N m^{-1}, and 9.78×10^{-4} Pa s, respectively. A spraying pressure of 0.3 MPa was achieved by using a tank with compressed air. A calibrated pressure gauge placed close to the nozzle ensured or required the operating liquid pressure.

Wind Tunnel

All sprays were measured in an open circuit wind tunnel located at the Gatton Campus of The University of Queensland. For PIV and droplet size tests, the working section was 1 m wide and 1 m high; for spray drift tests it was 1.75 m wide and 1.75 m high.

Spray Drift

Spray drifts at 2, 4, and 6 m downwind from each nozzle were collected on 2 mm diameter polythene lines following a proposed ISO standard (5682-1) for measurement of drift in the wind tunnel. At 4 and 6 m downwind from the tested nozzle, the lines were positioned 0.1 m above the wind tunnel floor; while at the distance of 2 m, five horizontal collector lines were mounted at heights of 0.1, 0.2 , 0.3, 0.4, and 0.5 m above the tunnel floor, to estimate the spray still airborne through this vertical plane. The wind speed was 2 m s^{-1}; Pyranine (D and C Green No. 8, Keystone Aniline Corporation, USA) fluorescent tracer was added to spray solution without changing the density, surface tension and viscosity, the concentration was 0.4 g l^{-1}. The samples were washed in 60 mL de-ionized water and then the tracer concentration was measured in a calibrated fluorometer (Turner-Sequoia model 450).

Atomization Process

Atomization process was recorded using a PIV system. The measurement zone was illuminated by an Nd: YAG PIV laser (Dantec-130 mJ), which could provide the two laser pulses required for PIV analysis. At the same time, a CCD camera (HiSense Mk ii, DANTEC) with a resolution of 1,344× 1,024 pixels and fitted with a 60 mm Micro Nikkor lens (Nikon, Japan), was used to image the complete spray breakup from the nozzle, including liquid sheet, ligaments and droplets. Figure 1 shows the experimental setup. A black sheet was used to cover the work section of the wind tunnel to get a dark background for the images (Figure 1-c). Timing of both the laser and camera was controlled by the Dantec Studio software. The interval between images in

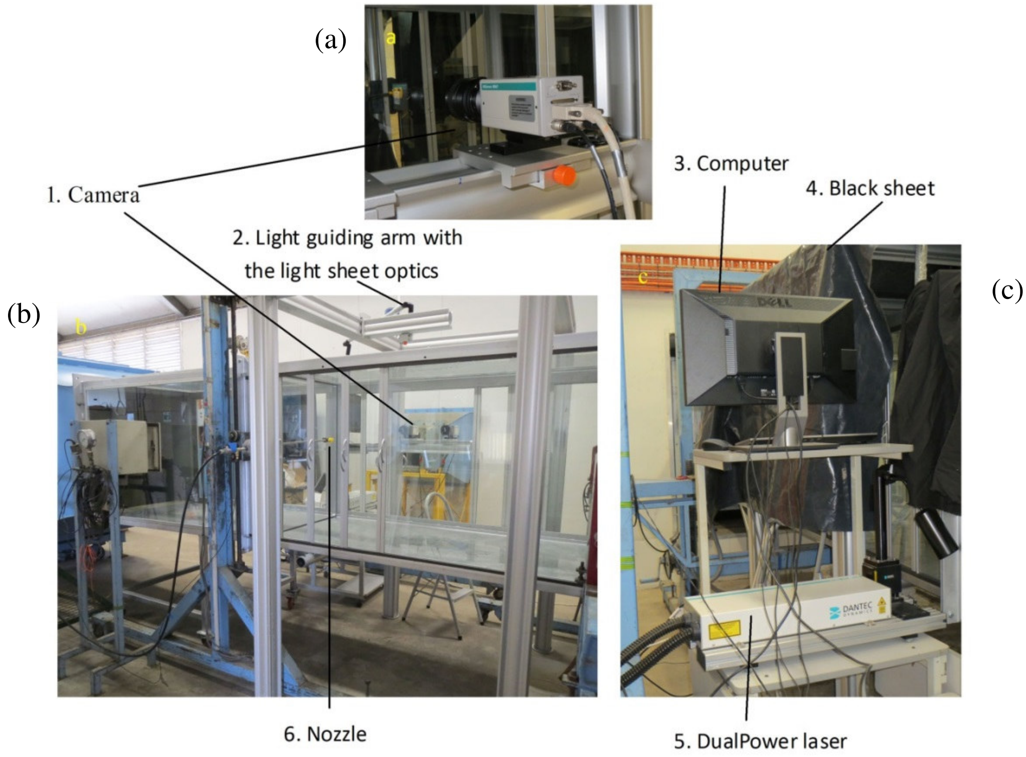


Figure 1. Experimental setup of PIV investigations: (a) Camera, (b) Working section of wind tunnel, (c) Control laser and computer part

each experiment was 100e-6 s. A total of 1,000 image pairs was recorded and used to calculate velocity for each spray.

Breakup Length

A public domain, Java-based image processing program (ImageJ 1.48c, developed at the National Institutes of Health) was used to measure the breakup length from the PIV images. The definition of breakup length in this study was the same as mentioned by Cloeter (2010) and defined as the distance from the nozzle tip to a point at which the sheet is completely broken apart over the entire spray angle. As the liquid film of hollow-cone nozzles (TR) was in the shape of hollow cone, its breakup length should be the average lateral height of the cone. PIV images only showed a section through the cone, therefore, the length of TR nozzles was calculated as the average of the upper and lower lateral heights displayed in the image; but for ST and IDK nozzles, the length was measured along the central line of the fan sheet. The breakup length measured from twenty separate images was averaged for each nozzle.

Velocity Field

After acquisition by the PIV system, the image pairs were firstly processed using Adaptive-Correlation. In this process, the image was discretized into small interrogation windows with a spatial resolution of 32×32 pixels to minimize the measurement uncertainty (Westerweel, 1997) and reduce the workload of analysis. The sample spacing between the centers of the interrogation windows was 16 pixels. As a result, 83×63 (horizontal by vertical) velocity vectors within the 1,344×1,024 pixel images were returned. To get real velocity, a calibration image with a ruler was used to calculate the ratio of pixel coordinates to real-world coordinates, consequently, the calculation was 0.058 mm $pixel^{-1}$ for both *x* and *y* (horizontal and vertical) directions. Transformed with this ratio, the FOV in the image was 78×59 mm. One velocity field was obtained by processing with each image pair and 1,000 fields were obtained for each nozzle. MATLAB® was used to deal with coordinates and velocity exported from Dantec Studio software to analyze droplet velocity. Incoherent velocity fields in those 1,000 image pairs were removed to compute a corrected average of velocity. A contour plot of the velocity field of the spray sheet for each nozzle was drawn by MATLAB® and the average velocities of the full field and the velocities along the center line of the image were calculated.

Spray Angle

The actual spray angle of each nozzle was measured using MATLAB® program, where the average light intensity of all images for each nozzle was calculated, this measured spray angle was an average of all images for every nozzle. The light intensity of liquid in the image was high, while the background was low, consequently, the calculation made the outer limits of spray sheet distinct with the background in dark blue. Two lines were drawn along the limits and the spray angle was taken as the angle between those two lines.

Velocity Fluctuation

Velocity fluctuation was used to show stability of the droplets velocity distribution. The average fluctuation of velocity, V', for each nozzle type was calculated by Equation (1), where u_i and v_i are the *x*- and *y*-component of velocity for the i^{th} field, respectively; $\bar{u}$ and $\bar{v}$ are their respective average; and *n* is the number of analyzed fields of the corresponding nozzle.

$$V' = \frac{1}{n}\sum_{i=1}^{n}\left[\left(u_i - \bar{u}\right)^2 + \left(v_i - \bar{v}\right)^2\right]^{1/2} \quad (1)$$

Droplet Size

Droplet size spectra generated by each nozzle was measured using a Sympatec Helos laser diffraction particle-size analyzer (Sympatec GmbH, Germany). Based on volume median diameter ($D_{v0.5}$) tested by Wang *et al*. (2014) at the operating pressure of 0.3 MPa, the ST110-02, ST110-03, TR80-02 and TR80-03 nozzles were classified into Fine category, the IDK120-02 nozzle was classified into Coarse category, and the IDK120-03 nozzle was classified into Very Coarse category, by ANSI/ASAE S572.1 standard (2009). According to the standard, the measurement point was 250 mm away from a nozzle, where there is full breakup of the spray sheet. Similar to the test of Dorr *et al*. (2013), airspeed in the wind tunnel was set to 6 m s^{-1}. Nozzle bodies were orientated parallel to the air stream and the long axis of the fan nozzles (IDK and ST nozzles) were orientated at an angle of 45° to the horizontal. The time of laser beam traversing through a spray sheet was about 10 seconds, to fulfil the requirement of minimum 2000 droplets by International Standard ISO 5682-1 (1996). Besides $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$, the fractions important for drift risk ($V_{<75}$ and $V_{<100}$) and for ground loss ($V_{>400}$) were also analyzed (Nuyttens *et al*., 2007; Sayinci *et al*., 2012).

Where,

$D_{v0.1}$, $D_{v0.5}$ *and* $D_{v0.9}$= Volume diameter (μm) below which smaller droplets constitute, respectively, 10, 50, and 90% of the total volume;

$V_{<75}$ *and* $V_{<100}$= Proportion of total volume of droplets smaller than 75 and 100 μm in diameter, ($\%_{vol.}$);

$V_{>400}$= Proportion of total volume of droplets larger than 400 μm, ($\%_{vol}$).

Statistical Analysis

A one-way analysis of variance (ANOVA) (IBM® SPSS® Statistics Version 20, IBM Corporation) was used to analyze the results. Fisher's Least Significance Difference (LSD) test was used to compare the statistical significant differences among nozzles, using α= 0.01 for each test.

RESULTS

Spray Drift

There were significant differences in spray drift between nozzles using α= 0.01, except for the spray drift positioned 0.5 m above the tunnel floor and 2 m downwind from nozzle (P= 0.016). Shown in Figure 2, the spray drift of IDK nozzles were the lowest, followed by TR and ST nozzles. For IDK and TR nozzles, the drift of 03 nozzle was a little lower than 02 (P> 0.035); for TR nozzles, the drift of 03 nozzle was significantly lower than 02 (P< 0.0005).

Atomization Process

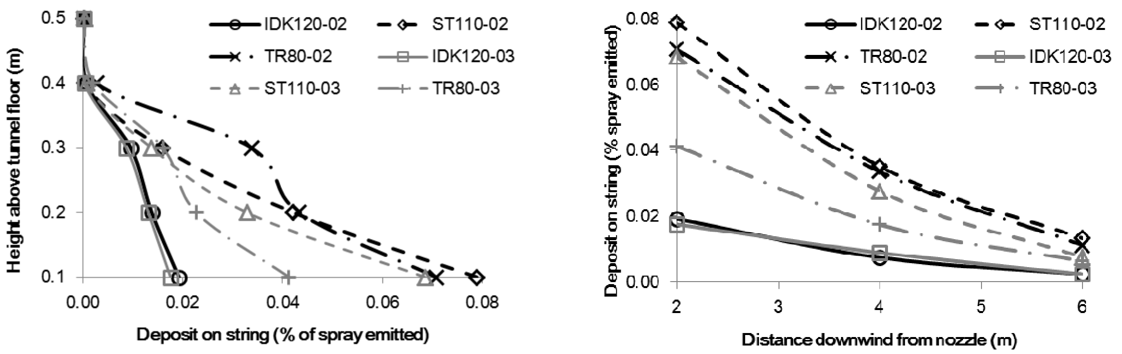
The atomization process was analyzed using the raw images captured by that camera. Examples of these PIV images are shown in Figure 3, with the corresponding nozzle types on the left side. Breakup modes of each nozzle type are shown in the images. For IDK nozzles, there were perforations in the liquid sheet leading to the generation of droplets earlier than ST and TR nozzles. This is due to air being sucked into the Venturi chamber of the IDK nozzles. For ST and TR nozzles, the breakups were found to start at the liquid rims of the sheets without holes in the liquid sheets. The liquid sheet of TR nozzle was hollow cone shaped.

Breakup Length

Breakup length shown in Figure 3 and listed in Table1 revealed that increasing the orifice size (higher flowrate) significantly (P< 0.0005) lengthened the breakup zone for each tested nozzle design, especially for ST nozzle, where the increment of length was 23% for the 03 nozzle compared to the 02.

Velocity Field

The contours of the velocity magnitude are shown in Figure 4, revealing the velocity distribution of the sheet. Velocity color scales were normalized with dark red indicating the highest velocity (23.73 m s^{-1}), and dark blue the lowest velocity (5.32 m s^{-1}). Those two velocities were the limits of all calculated average velocity fields. The average velocity is listed in Table 1. It was found that velocity



(a) (b)

Figure 2. Spray drift from each type of tested nozzle in a 2 m s^{-1} air stream as measured in a wind tunnel. (a) Spray airborne (drift) 2 m downwind from nozzle, (b) Spray drifts at 2, 4, and 6 m downwind from each nozzle were collected on string positioned 0.1 m above the wind tunnel floor.

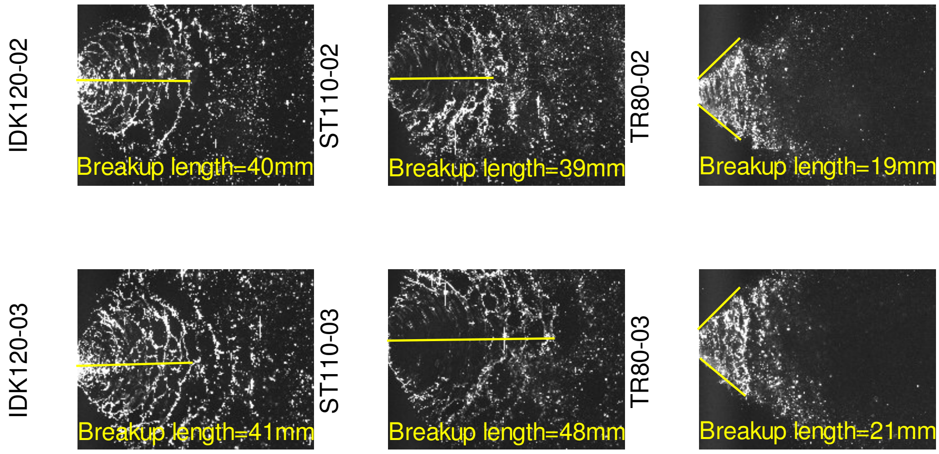


Figure 3. Atomization of each type of nozzle imaged by PIV with the annotation of breakup length.

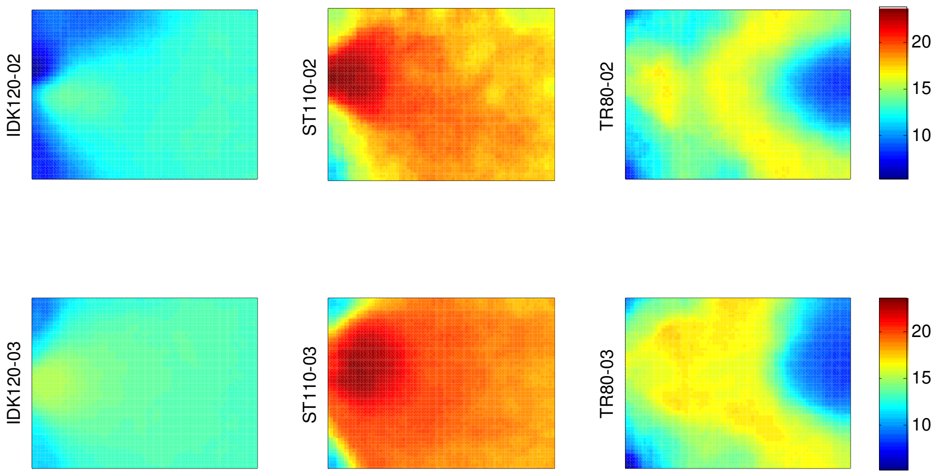


Figure 4. Distribution contours of the droplets velocity magnitude (m s^{-1}) for the six nozzle types. All velocity color scales were normalized with dark red indicating 23.73 m s^{-1} and dark blue 5.32 m s^{-1}.

Table 1. Results of breakup length, spray angle, and droplets velocity, etc. for each nozzle.

Results	Nozzle type[a]					
	IDK02	ST02	TR02	IDK03	ST03	TR03
Breakup length (mm)	40^{B}	39^{B}	19^{C}	41^{B}	48^{A}	21^{C}
Average velocity (m s^{-1})	11.94^{F}	18.49^{B}	14.12^{C}	13.42^{E}	19.37^{A}	14.51^{C}
Spray angle (°)	115^{B}	116^{AB}	85^{C}	116^{AB}	119^{A}	85^{C}
Average fluctuation (m s^{-1})	2.75^{E}	4.54^{A}	3.93^{B}	1.61^{F}	3.23^{C}	2.98^{D}

[a] The nozzle type, IDK120-02, ST110-02, TR80-02, IDK120-03, ST110-03 and TR80-03, were abbreviated to IDK02, IDK03, ST02, ST03, TR02 and TR03, respectively. Letters are used to indicate significant differences between nozzles as determined by the ANOVA and Fisher's LSD test using α= 0.01.

distributions were significantly different among nozzle types (P< 0.0005). Droplets sprayed from ST nozzle were the fastest followed by TR and IDK nozzles with the same orifice size (i.e., with the same nominal flow rate) in turn. For the same design nozzles, droplets sprayed from 03 nozzles moved significantly faster than those of 02 nozzles.

Figure 5 shows the velocity profile along the central axis of the spray plume. In general, the velocity decreased with increasing distance from nozzle, especially for ST nozzles. The curves of TR nozzles dropped rapidly at 50 mm or more away from the nozzle due to the cone sheets being hollow.

Spray Angle

In Figure 6, the actual measured spray angles are shown on their corresponding contour of the average light intensity where the outer edges (marked with yellow lines) of spray sheet are shown distinctly, the outside of spray sheet is in dark blue. Spray angle values are listed in Table 1. For the tested nozzles, the measured spray angles were found to be different from the nominal values; however, the relative differences were smaller than 10%. Different from the nominal values, there was no significant difference between the actual spray angle of IDK and ST nozzles with the same orifice

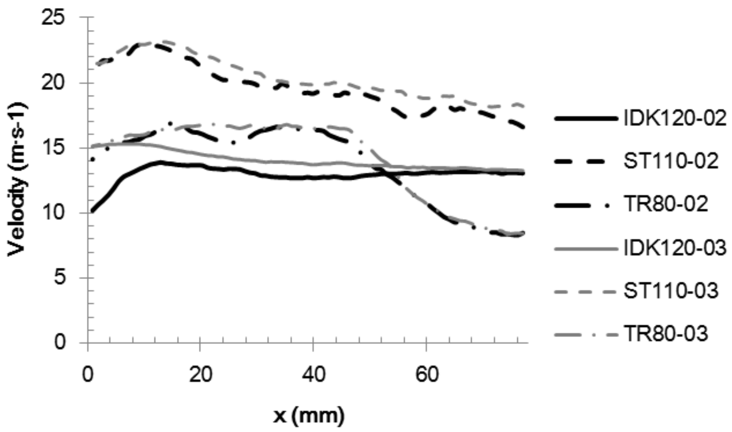


Figure 5. Droplets velocity profile along the central axis of the spray plume (y= 0 mm).

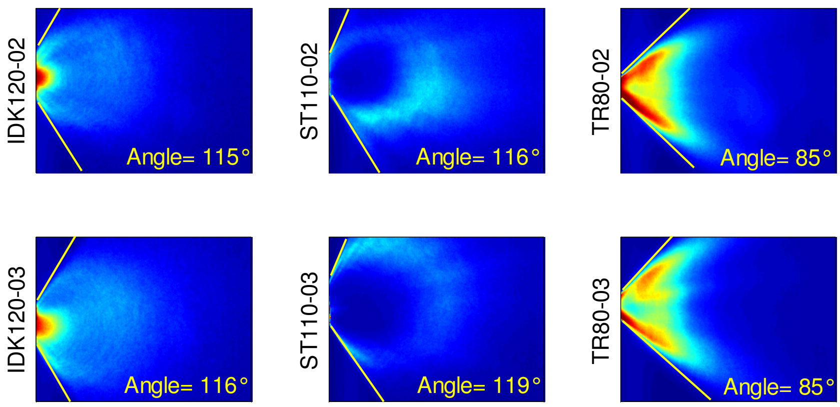


Figure 6. Measured spray angle of each type of nozzle. Every angle is shown on its corresponding contour of the average light intensity, where the outer edges (marked with yellow lines) of spray sheet are distinctly shown. The outside of spray sheet is in dark blue.

size. For the same design, spray angles of different orifice size nozzles were similar in accord with the manufactory's expectation.

Velocity Fluctuation

Based on the calculation of velocity fluctuation using Equation (1), the velocity fluctuation distributions in Figure 7 revealed how the velocity at any position in the FOV varies with time. The velocity field with small fluctuation is stable. The maximum fluctuation shown in dark red is 11.40 m s^{-1} and the minimum in dark blue is 0.98 m s^{-1} (Table 1). Analyzed with the Fisher's LSD test, fluctuations were found to be significantly different among nozzles ($P< 0.0005$), velocity fields of 03 nozzles were more stable than those of 02 nozzles for all nozzle designs tested. The velocity field of ST nozzle was the most unstable followed by TR and IDK nozzles with the same orifice size. Considered together with Figures 2 and 3, it was found that velocity distributions of both ST110-02 and TR80-02 nozzles were relatively unstable. This may be due to droplets moving out of the main spray sheet in some image pairs; the velocities of those droplets were counted in.

Droplet Size

Spray droplet size has been found to be a predominant factor contributing to the potential for drift in conventional application systems (Qin *et al.*, 2010). Droplet size measurements listed in Table 2 were subjected to ANOVA and Fisher's LSD test (α= 0.01). They were significantly different among nozzles ($P< 0.0005$). Shown by $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$, droplet sizes of 03 nozzles were significantly larger than those of 02 nozzles with the same nozzle design. Generally, droplet sizes of IDK nozzles were comparatively larger than those of the other nozzles. $V_{<75}$ and $V_{<100}$ of IDK nozzles were considerably less than ST and TR nozzles leading to lower drift risk; however, $V_{>400}$ of IDK nozzle was obviously higher than the others, revealing that more ground losses may result when using IDK nozzle, especially the IDK120-03 nozzle.

DISCUSSION

The results showed that nozzle types significantly influenced spray drift, droplet size and velocity, spray angle, and breakup length. Velocity from the compact air–

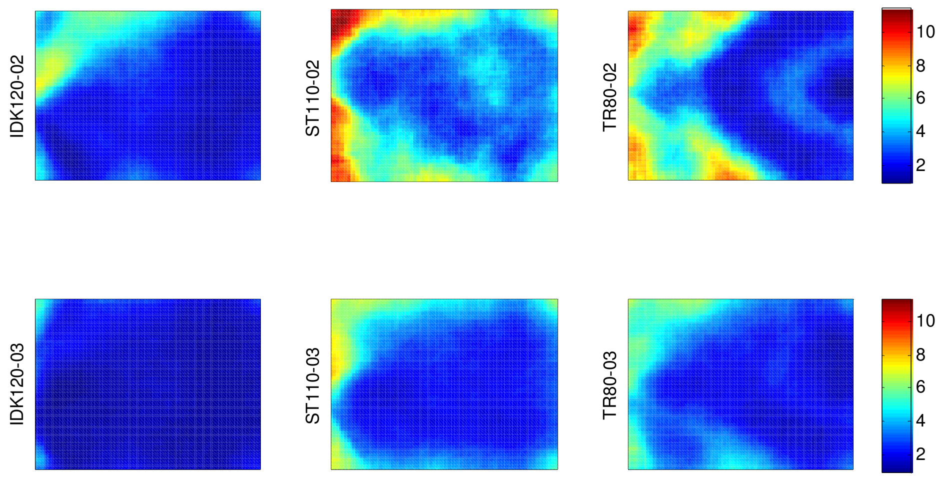


Figure7. Distribution contours of velocity fluctuation of six nozzle types. The maximum fluctuation in dark red is 11.40 m s^{-1}, the minimum in dark blue is 0.98 m s^{-1}. High velocity fluctuation in this figure means big velocity difference of droplets which arrive at the same place at different times.

Table 2. Result of droplet size for each nozzle.[a]

Results	Nozzle type					
	IDK120-02	ST110-02	TR80-02	IDK120-03	ST110-03	TR80-03
$D_{v0.1}$ (μm)	165 B	73 C	65 D	181 A	76 C	80 C
$D_{v0.5}$ (μm)	351 B	171 D	147 E	419 A	173 D	185 C
$D_{v0.9}$ (μm)	584 B	303 D	246 E	695 A	299 D	323 C
$V_{<75}$ ($\%_{vol.}$)	1.38 C	11.36 AB	13.31 A	1.26 C	9.70 B	8.61 B
$V_{<100}$ ($\%_{vol.}$)	2.61 D	19.65 B	24.69 A	2.27 D	18.45 B	16.08 C
$V_{>400}$ ($\%_{vol.}$)	38.62 B	1.91 C	0.12 C	53.88 A	0.70 C	2.76 C

[a] Letters are used to indicate significant differences between nozzles as determined by the ANOVA and Fisher's LSD test using α= 0.01, (P< 0.0005).

induction IDK flat fan nozzles were lower than that of the conventional hydraulic pressure ST and TR nozzles, agreeing well with the results of Miller *et al*. (2008). The mean droplets velocity calculated by Miller *et al*. (2008) was the average velocity of all droplets at the spray height of 350 mm, while the average velocity of droplets in this study was the average of velocity field in the entire FOV within 78 mm from nozzle tip, as a result, these average droplets velocities of Miller *et al*. (2008) were lower than those of this study based on the trend shown in Figure 5.

According to the trend of each tested parameter, it was found that:

(1) Nozzles with a longer sheet breakup or wider spray angle produced smaller droplets, agreeing with the opinions of Arvidsson *et al*. (2011). This is because droplet sizes were mostly close to the thickness of the sheet from which they were formed (Hilz and Vermeer, 2013), however, the functional relationship of sheet thickness to length and angle needs further study. For the IDK nozzle, the air that is sucked into the Venturi chamber of IDK nozzle, could in principle break the liquid film in the center of the spray sheet (similar to emulsions described by Cloeter *et al*. (2010)), where the film is thicker than with the ST nozzle whose droplets form at the rim.

(2) Nozzles produced larger droplets at lower velocities. This relationship may be relative to the conservation of kinetic energy, yet the definite relation between droplet size and droplet velocity based on the conservation still needs further research and is out of the scope of this study.

(3) Nozzles generating coarser droplets had lower droplets velocity fluctuation, i.e. more stable velocity fields during atomization process, because velocities of bigger droplets were less influenced by environmental conditions such as wind speed.

(4) Spray drift was significantly correlated with droplet sizes and droplets velocities, especially with $V_{<75}$ and $V_{<100}$ specific droplet size fractions. The IDK nozzle caused a very low spray drift based on large droplets and low droplets velocity fluctuation. Spray drift was correlated with nozzle type. Nozzle configuration influenced breakup length and spray angle resulting in the formation of droplets with different sizes and velocities.

CONCLUSIONS

In this study, the influence of nozzle type on spray drift was investigated. The atomization processes of six nozzle types typically used for spraying cotton in China were visualized and studied by using a PIV system and image-processing software. Parameters such as breakup length, spray angle, droplet size, droplets velocity distribution, and droplets velocity fluctuation were used to explain the influence of nozzle type on spray characteristics and spray drift. The conclusions are as follows:

(1) Different nozzle designs have different breakup modes. The compact air-induction flat fan nozzles (IDK) spraying water started to breakup in the center of the liquid sheet due to the air sucked into the Venturi chamber of the nozzle.

(2) Compared to ST and TR nozzles, IDK nozzles produced droplets with larger diameter, lower velocity, and less velocity fluctuation (i.e., more stable spray). Stable velocity distribution is conducive to keep deposition uniform, because velocity is one important parameter to determine whether droplet adheres on the target or not (Dorr *et al*., 2014).

(3) Spray drift was significantly correlated with nozzle type. The IDK nozzle generating larger and slower droplets resulted in less spray drift than ST and TR nozzles.

(4) As the atomization process is also influenced by the physical properties of the sprayed liquid, the effects of spray solution properties on spray drift will be considered in the future studies.

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عملکرد نازل های پاششی منتخب با استفاده از سرعت سنجی تصویری ذرات

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چکیده

هدف این پژوهش بررسی اثر ویژگی های نازل روی باد بردگی ذرات بود و توضیح اثرات آن با استفاده از ویژگی های دستگاه ذره ساز(شامل طول صفحه پاشش، زاویه پاشش، توزیع سرعت میدان جریان، تغییرات سرعت، و اندازه ریزقطره ها). به این منظور، نازل های ساخت یک کارخانه (Lechler GmbH, Germany) با پاشیدن آب معمولی در یک تونل باد در فشار عملیاتی برابر ۰/۳۰ مگا پاسکال و در درجه حرارت اطاق مورد آزمون قرار گرفتند. نازل های آزمون شده از نوع جمع وجور و هوا-القا با نازل مسطح (IDK120-02 و IDK120-03) و نازل های مسطح استاندارد (ST110-02 وST110-03) و نازل های گردونی مخروطی درون تهی (TR80-02 و TR80-03) بودند. برای ثبت فرایند ذره سازی (atomization) از روش سرعت سنجی تصویری ذرات (Particle Image Velocimetry) استفاده شد، اندازه ریزقطره ها با دستگاه Sympatec Helos برای اندازه گیری ذرات به روش انحراف لیزری تعیین شد، و اندازه گیری باد بردگی ذرات پاشیده شده در تونل باد و اندازه گیری نهشته ها با دستگاه فلورسنس سنج واسنجی شده (Turner-Sequoia model 450) انجام شد.نتایج نشان داد که بادبردگی ذرات نازل های مختلف به طور معنی داری (P<0.0005) متفاوت بود و ویژگی های نازل روی طول محل فرود ذرات ، زاویه پاشش، اندازه ریزقطره ها، و سرعت حرکت اثر داشت.نازل هایی که ریزقطره های درشت تری ایجاد می کردند سرعت حرکت کمتری داشتند در حالی که ریزقطره های کوچک تر هنگامی ایجاد می شدند که صفحه پاشش عریض تر بود. در مقایسه با نازل های مدل ST وTR ، افشانک IDK در مرکز صفحه مایع جدا شدن را آغاز می کردند و در نتیجه ریزقطره های درشت تر با سرعت کمتر و نوسان کمتر در سرعت ایجاد می شد. بنا بر این نتایج، نازل IDK که بادبردگی کمتری در باد های سریع تر دارد انتخاب بهتری است.