Article

Analysis of the Influence of Different Parameters on Droplet Characteristics and Droplet Size Classification Categories for Air Induction Nozzle

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Abstract: Droplet characteristics are identified as essential factors in agricultural spray application. The aims of this study were to analyse the influence of spray parameters on droplet characteristics and to determine possible candidate sprays that would produce the same droplet size categorizations as the American Society of Agricultural and Biological Engineers (ASABE) standard S-572.1 for air induction nozzles (AINs). Six different orifice sizes of the Billerica Farm Services (BFS) air induction (AI) flat fan hydraulic nozzles (the air bubblejet) were examined at different spray pressures (200 kPa, 300 kPa, 400 kPa, 500 kPa, 600 kPa and 700 kPa) and concurrent air velocities (2 m/s, 3 m/s, 4 m/s and 5 m/s). The influences of spray parameters on the droplet characteristics were analysed using analysis of covariance (ANCOVA) and analysis of variance (ANOVA). Results showed that: (1) The values of droplet characteristics and the results of ANOVA were significantly different before and after eliminate the influence of dynamic surface tension (DST) on droplet characteristics by ANCOVA; (2) (a) the reduction rates of the droplet diameter sizes decreased with increasing spray pressure; (b) air velocities of 2 m/s and 5 m/s resulted in smaller droplets reports, and air velocities of 3 m/s and 4 m/s are more suitable for agricultural spray applications; (c) a larger nozzle orifice size not always result in a larger droplet size and (3) Fine, Medium, Coarse, Very Coarse and Extremely Coarse droplet classification categories as the ASABE S-572.1 standard categorizations were determined to classify AINs.

Keywords: wind tunnel; air induction nozzle; droplet characteristics; droplet size classification category; ASABE S-572.1

1. Introduction

Pesticides continue to be critical management tools for pests, weeds, insects and diseases in crop protection [1]. Society's preoccupation with the use of pesticides in plant protection has increased with time. Sufficient deposition and uniform distribution of active materials on target plant surfaces are the main goals in pesticide spray applications [2]. Maximizing spray efficiency and minimizing

spray drift to non-target areas are crucial considerations when undertaking spray applications. Air induction nozzles (AINs) produce larger droplets than traditional nozzles and were developed for spray efficiency improvement and spray drift reduction [3], especially for herbicide applications.

Droplet size is a major determinant of effective deposition and drift potential of liquid sprays [4]. Droplet size is affected by the chemical and physical properties of spray liquid, such as dynamic surface tension (DST), and other parameters, such as nozzle type and orifice size, spray pressure and air velocity [5,6]. Understanding the influence of spray parameters on droplet characteristics can help improve spray efficacy and reduce drift by parameters selecting in agricultural spray applications [7]. Previous studies [7–9] showed that droplet size increased with an increase in nozzle orifice size and decreased with an increase in the spray pressure. Tang et al. [10] tested four air induction (AI) nozzles in a high-speed wind tunnel at seven different air velocities (from 121.7 to 305.5 km·h⁻¹). They found that the $D_{v0.1}$ and $D_{v0.5}$ decreased quasi-linearly with increased wind speed, while $D_{v0.9}$ was affected by quadratic wind speed. The $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ were all proportional to the orifice size and were not markedly influenced by the spray pressure. Dynamic surface tension (DST) is an important physical property of the spray liquid [11], and is influenced by the temperature and chemical property of the solution. Zhao et al. [12] tested a series of flat fan nozzles and observed that there was a positive linear correlation between $D_{v0.5}$ and DST. Studies have reported that the DST of liquid decreased with increasing liquid temperature [13,14], which resulted in smaller droplets [15]. Miller et al. [16] observed that the droplet size of flat fan nozzles decreased as the liquid temperature increased from 15 °C to approximately 25 °C.

A classification of sprays based on droplet size has been used to classify nozzles in relation to spray efficacy and drift potential [17]. The British Crop Protection Council (BCPC) developed a standard to classify droplet size, which has since been updated and approved under the American Society of Agricultural and Biological Engineers (ASABE). In 2009, the S-572.1 standard was produced by the ASABE, and the droplet size classes were determined according to the S-572.1 standard, which are shown as follows in ascending order: Extremely Fine, Very Fine, Fine, Medium, Coarse, Very Coarse, Extremely Coarse, and Ultra-Coarse [18]. De Schamphellerie et al. [19] classified 10 Hardi nozzles of different types and sizes based on the BCPC reference system. However, due to multiple diffraction phenomena, the spectra of the AIN were not successfully measured and classified. Czaczyk et al. [20] tested ceramic air induction flat fan nozzles of the Albus AVI series (Coors Tek, inc., Le Havre, France) with orifice sizes of 01, 02 and 03 to classify AINs based on the ASABE S-572.1 standard. Thus far, the application of the system for the classification of AIN sprays has been somewhat limited. However, AIN sprays are routinely classified with appropriate classification categories of normal flat fan nozzles based on the ASABE reference.

This study aimed to (1) report more details about how the droplet nozzle orifice size, spray pressure and air velocity influence the droplet characteristics of AINs under low air velocity conditions, such as: (a) How the droplet size decreases with the increase of spray pressure, (b) how the droplet size increases with the increase of nozzle orifice size and (c) how the droplet size change with the air velocity, and to (2) determine possible candidate sprays that would produce the same droplet size categories as the ASABE S-572.1 reference categories for AINs.

2. Materials and Methods

2.1. Wind Tunnel Facilities

This study was carried out at the ground application wind tunnel research facility in the Centre for Pesticide Application and Safety (C-PAS) at the University of Queensland in Gatton, Queensland, Australia. The wind tunnel test system includes a traversing liquid delivery, an atomization system, a laser diffraction particle size analyser and a data storage and processing system. The droplet size spectra of each spray were measured by a Helos-Vario laser diffraction system with an R7 lens (Sympatec Inc., Clausthal, Germany). The laser was controlled by Windox 5.70 software operated on

a computer. The test nozzles were oriented upright. All measurements were replicated at least three times until the $D_{v0.5}$ values were within instrument repeatability (i.e., ± 3) [21]. Each replicate was measured for 9 s to provide sufficient time to measure the whole spray sheet. The schematic, setup geometry and configuration of wind tunnel test system are shown in Figure 1a,b.

Figure 1. (a) The schematic of wind tunnel test system [22]. (b) The setup geometry and configuration of wind tunnel facilities. Note: The test nozzles were mounted on a vertical movement actuator, which was controlled by a programmable logic controller (PLC) to move the nozzle body at a constant speed. The Helos laser diffraction system had a horizontal distance of 51 cm downwind of the test nozzles, which was sufficient for the breakup of the liquid sheet.

2.2. Dynamic Surface Tension (DST) Measurements

The water temperature changes as the ambient temperature changes. The ambient temperature changes between different days and during the day from morning to afternoon. Based on the theories of previous studies [20,23] and the ASABE S-572.1 standard [18], tap water at ambient temperature was used for the spray tests in this study. The water temperature changed from 22 °C to 31 °C in this study. The change in water temperature led to a change in dynamic surface tension (DST), and the change in DST led to a change in droplet characteristics. The DST data for each treatment were measured by a bubble pressure tensiometer (BP-2) (Kruss GmbH, Hamburg, Germany) at 20 ms. Measurement was performed three times to produce a mean value of DST for each treatment.

2.3. Atomizers

Six different orifice sizes of the Billerica Farm Services (BFS) air bubblejet AI flat fan nozzles (BFS 11001, 11002, 11004, 11005, 11006, 11008) with nozzle sizes of 01, 02, 04, 05, 06 and 08, respectively, were examined. Spray pressures of 200 kPa, 300 kPa, 400 kPa, 500 kPa, 600 kPa and 700 kPa and air velocities of 2 m/s, 3 m/s, 4 m/s and 5 m/s were set up. The XR 11003VS was also measured by a method consistent with the ASABE S-572.1 standard in the same laboratory, and it has been used as the ASABE reference nozzle in international spray studies [24–26]. The criteria of the size classes were provided by a set of certified reference nozzles.

2.4. Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) was carried out using a confidence interval of 95%, and the mean separation was made at the $p = 0.05$ level. SPSS 25.0 was employed to perform ANOVA to analyse the influence of spray pressure, air velocity and nozzle orifice size on $D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$, the proportion of spray volume contained in droplets with a diameter below 150 μm ($\% < 150 \mu\text{m}$), relative span

(RS) and coefficient of variance (CV). F and P values were used, as they are very important indices for assessing ANOVA results [27].

2.5. Analysis of Covariance (ANCOVA)

Covariates are variables in experiments that affect responses but are not of direct interest and cannot be controlled during the design of the experiment. Analysis of covariance (ANCOVA) is used to adjust the dependent variable by removing the influence of a covariate on it and increase the statistical power by reducing within-group error variance [28]. In the present study, DST of water influenced droplet characteristics, but it was not controllable. ANCOVA was carried out by using SPSS 25.0 to eliminate the influence of DST on measured values and obtain the calibrated values of droplet characteristics for data analysis in this study.

3. Results and Discussion

3.1. Influence Analysis

The analysis results for the influences of spray pressure, air velocity and nozzle orifice size on droplet characteristics are shown in Table 1.

Table 1. The influences of spray pressure, air velocity and nozzle orifice size on the droplet characteristics of $D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$, % < 150 μm , relative span (RS) and coefficient of variance (CV) were analysed by analysis of variance (ANOVA) using SPSS 25.0. F: Variance of the group mean; p -value: The probability of obtaining the observed results; NS: Not significant, *: Significant, and **: Highly significant.

Influence Parameter	Droplet Characteristics	F	p -Value	Significance
Spray pressure	$D_{v0.1}$	9.225	0.000	**
	$D_{v0.5}$	11.461	0.000	**
	$D_{v0.9}$	8.293	0.000	**
	% < 150 μm	9.464	0.000	**
	RS	1.513	0.219	NS
	CV	0.746	0.528	NS
Air velocity	$D_{v0.1}$	0.996	0.375	NS
	$D_{v0.5}$	1.372	0.260	NS
	$D_{v0.9}$	0.998	0.374	NS
	% < 150 μm	1.523	0.225	NS
	RS	1.593	0.211	NS
	CV	0.882	0.419	NS
Nozzle orifice size	$D_{v0.1}$	19.854	0.000	**
	$D_{v0.5}$	17.222	0.000	**
	$D_{v0.9}$	24.272	0.000	**
	% < 150 μm	16.650	0.000	**
	RS	0.398	0.000	**
	CV	1.717	0.143	NS

As illustrated in Table 1: (1) Spray pressure had a highly significant influence on $D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$ and % < 150 μm ($p < 0.01$) and had no significant influence on RS and CV ($p > 0.05$), (2) air velocity (ranges from 2 m/s to 5 m/s) had no significant influence on any of the droplet characteristics investigated in this study ($p > 0.05$) and (3) nozzle orifice size had a highly significant influence on $D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$, % < 150 μm and RS ($p < 0.01$) and had no significant influence on CV ($p > 0.05$).

There was a contrast between this study and previous studies [10,15] that have reported that the air velocity had a significant influence on droplet characteristics. The reason might be that, except for the variables of spray pressure, air velocity and nozzle orifice size, the measured values of droplet characteristics were influenced by the covariate of DST. Some DST values of different water temperatures are shown in Table 2.

Table 2. Some dynamic surface tension (DST) values of different water temperatures.

Temperature/°C	Dynamic Surface Tension/Dyn·cm ⁻¹	Temperature/°C	Dynamic Surface Tension/Dyn·cm ⁻¹
22.5	72.32	27.6	71.40
23.4	72.13	28.3	71.25
24.7	71.97	29.5	71.01
25.2	71.63	30.2	70.82
26.8	71.52	31.0	70.56

The values of droplet characteristics before and after ANCOVA were compared by SPSS using a paired t-test to observe if there were significant differences between the values of droplet characteristics before and after ANCOVA. The compared results are shown in Table 3.

Table 3. The t-test values of droplet characteristic values before and after analysis of covariance (ANCOVA). P-value: The probability of obtaining the observed results; NS: Not significant, *: Significant, and **: Highly significant.

Droplet Characteristics	Paired Difference				p-Value (2-Tailed)	Sig.
	Mean	Std. Deviation	Std. Error Mean	t		
D _{v0.1}	4.5923	15.888	1.872	2.453	0.017	*
D _{v0.5}	4.1810	16.213	1.911	2.188	0.032	*
D _{v0.9}	13.0807	22.677	2.672	4.895	0.000	**
% < 150 µm	2.095	2.056	0.242	8.646	0.000	**
RS	0.384	1.950	0.230	1.671	0.099	NS
CV	0.035	0.463	0.055	0.645	0.521	NS

As shown in Table 3, before and after ANCOVA, (1) the values of D_{v0.1} and D_{v0.5} were significantly different, (2) the values of D_{v0.9} and % < 150 µm were highly significantly different and (3) the differences between RS and CV values were not significant. These results suggest that because some of the droplet characteristic values were changed significantly by ANCOVA, the influence of spray parameters on droplet characteristics should be re-analysed.

The analysis results of the influence of spray pressure, air velocity and nozzle orifice on droplet characteristics after ANCOVA are shown in Table 4.

Table 4. The influence of parameters on droplet characteristics after ANCOVA. F: Variance of the group mean; p-value: The probability of obtaining the observed results; NS: Not significant, and *: Significant.

Influence Parameter	Droplet Characteristics	F	P	Sig.
Spray pressure	D _{v0.1}	17.454	0.003	*
	D _{v0.5}	11.505	0.009	*
	D _{v0.9}	14.833	0.005	*
	% < 150 µm	8.322	0.019	*
	RS	2.964	0.127	NS
	CV	0.657	0.521	NS
Air velocity	D _{v0.1}	0.074	0.013	*
	D _{v0.5}	0.559	0.03	*
	D _{v0.9}	0.415	0.017	*
	% < 150 µm	0.610	0.047	*
	RS	0.922	0.448	NS
	CV	2.329	0.178	NS
Nozzle orifice size	D _{v0.1}	1.061	0.035	*
	D _{v0.5}	1.139	0.035	*
	D _{v0.9}	1.396	0.029	*
	% < 150 µm	0.869	0.039	*
	RS	0.76	0.494	NS
	CV	0.494	0.513	NS

Table 4 shows that after ANCOVA, spray pressure, air velocity and nozzle orifice size had significant influences on $D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$ and $\% < 150 \mu\text{m}$, and had no significant influence on RS and CV. These results are more logical because many studies have shown that air velocity has a significant influence on droplet characteristics [10,15]. Therefore, the values of droplet characteristics, which were calibrated by ANCOVA, were used for data analysis in this study.

The volumetric droplet diameters and proportion of spray volume contained in droplets with a diameter below $150 \mu\text{m}$ ($\% < 150 \mu\text{m}$) for the different BFS nozzles under different spray pressures and air velocities are shown in Figures 2–4.

Figure 2. (a) Volumetric diameters below which smaller droplets constitute 10%, 50% and 90% of the total spray volume ($D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$) and (b) proportion of the spray volume contained in droplets with a diameter below $150 \mu\text{m}$ ($\% < 150 \mu\text{m}$) for 11001 under different spray pressures (200–700 kPa) at an air velocity of 3 m/s.

Figure 3. (a) Volume diameters below which smaller droplets constitute 10%, 50% and 90% of the total spray volume ($D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$), and (b) proportion of spray volume contained in droplets with a diameter below $150 \mu\text{m}$ ($\% < 150 \mu\text{m}$) for 11001 under different air velocities (2–5 $\text{m}\cdot\text{s}^{-1}$) at 400 kPa.

Figure 2a shows that the results obtained in this study were similar to those in previous reports [29–31], which showed the droplet diameter size decreased with increasing spray pressure. More details were observed in this study as follows: (1) When spray pressure increased from 200 kPa to 300 kPa, $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ decreased 16.1%, 15.8% and 14.4%, respectively; (2) when spray pressure increased from 300 kPa to 400 kPa, $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ decreased 14.0%, 15.4% and 13.3%, respectively; (3) when spray pressure increased from 400 kPa to 500 kPa, $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ decreased 8.6%, 11.2%

and 10.4%, respectively; (4) when spray pressure increased from 500 kPa to 600 kPa, $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ decreased 6.0%, 7.9% and 7.7%, respectively; (5) when spray pressure increased from 600 kPa to 700 kPa, $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ decreased 2.5%, 3.0% and 2.3%, respectively. It can be concluded that for 11001 at an air velocity of 3 m/s, the reduction rates of the droplet diameter size ($D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$) decreased with increasing spray pressure. The same results were observed by the other tested nozzles.

Figure 2b shows that for a nozzle with a given orifice diameter size and air velocity, % < 150 μm increased with increasing spray pressure. When the spray pressure increased from 300 kPa to 400 kPa, 400 kPa to 500 kPa, 500 kPa to 600 kPa and 600 kPa to 700 kPa, % < 150 μm increased by 3.76%, 3.45%, 1.02% and 0.63%, respectively. The increase rate of the % < 150 μm values decreased with increasing spray pressure. The difference in % < 150 μm values between 600 kPa and 700 kPa was rather limited (0.63%). However, the increase rate of % < 150 μm from 200 kPa to 300 kPa (3.08%) was observed to be smaller than that from 300 kPa to 400 kPa, and 400 kPa to 500 kPa. The reason might be that it was difficult to operate at 200 kPa for 11001, causing the values of the droplet characteristics to be abnormal. Therefore, we moved the laser be closer to (30 cm away from) the nozzle to test 11001 at 200 kPa. Compare with the distance of 51 cm, more small droplets were suspended and measured by the laser beam, and these proportion of small droplets were decelerated and did not reach the measuring area of 51 cm distance. This increased the measured value of % < 150 μm at 200 kPa, and therefore decreased the increase rate of % < 150 μm from 200 kPa to 300 kPa.

Figure 4. (a) Volume diameters below which smaller droplets constituted 10%, 50% and 90% of the total spray volume ($D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$), and (b) proportion of spray volume contained in droplets with a diameter below 150 μm (% < 150 μm) of nozzles with different orifice sizes at 400 kPa and 3 m/s.

The above results indicate that when the spray pressure increases from 700 kPa to 800 kPa, the decrease in droplet size would be within 3%, and % < 150 μm would be very limited (less than 1%). Based on the set criterion that the deviation in droplet size within 3% could be ignored (Hirleman et al., 1991), it is not necessary to operate spraying under a spray pressure of 700 kPa or higher. These results are important because sometimes it is not easy to obtain a spray pressure greater than 700 kPa for sprays, especially for nozzles with large orifice diameter sizes. Therefore, in this study, because it was not possible to operate nozzle sprays at 700 kPa, nozzles were not operated at 700 kPa (except for 11001).

Figure 3a presents the $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ of the 11001 nozzle at 400 kPa under different air velocities. At 2 m/s, the smaller droplets decelerated much more quickly than the larger droplets, and they were suspended over the measuring area and measured by the laser beam repeatedly. When the air velocity increased from 2 m/s to 3 m/s, the deceleration speed between small and large droplets was reduced, and the portion of suspended small droplets was blown away from the measurement area, which increased the reported mean droplet size and obtained a more accurate measurement of droplet

size values. When the air velocity increased from 4 m/s to 5 m/s, some large droplets, as well as small droplets, were blown away from the measurement area, and air shear also resulted in the secondary breakup of droplets [32], causing a decrease in the reported droplet size. Figure 3b shows the net effect, where the proportion of small droplets ($\% < 150 \mu\text{m}$) decreased 2.31% when the air velocity increased from 2 m/s to 3 m/s and increased 6.06% when the air velocity increased from 4 m/s to 5 m/s. The difference in the measured $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ values were rather limited (3.06 μm , 2.11 μm and 8.97 μm), and $\% < 150 \mu\text{m}$ values (0.35%) were negligible between 3 m/s and 4 m/s.

This study suggests that air velocities of 3 m/s and 4 m/s are more appropriate for agricultural spraying than 2 m/s and 5 m/s. The reasons are as follows: (1) First, the 2 m/s air velocity results in the suspension of fine droplets, and the laser beam measures them repeatedly, resulting in a smaller droplet size being reported. In field studies, fine droplet suspension is adverse for agricultural spraying because the suspended droplets would drift to the undesired area or evaporate into the air finally. (2) Second, in contrast, an air velocity of 5 m/s is too strong and would result in the secondary breakup of the larger droplets, blow droplets downwind and lead to serious spray drift.

Generally, for a given spray pressure and air velocity, larger nozzle orifice diameter would result in larger droplet size. However, it was observed in this study that a larger nozzle orifice size did not always produce larger size droplets. As shown in Figure 4a, at a spray pressure of 400 kPa and air velocity of 3 m/s, the $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ values for 11002 were 9 μm , 17 μm and 5 μm , respectively, which were lower than those values for 11001, and the values for 11006 were only 0.7, μm , 9.1 μm , and 7.78 μm , respectively, which were higher than those values for 11005. The same results can be obtained for $\% < 150 \mu\text{m}$ (Figure 4b). The $\% < 150 \mu\text{m}$ value for 11002 was 2.73% higher than that for 11001, and the $\% < 150 \mu\text{m}$ value for 11005 was slightly higher (0.08%) than that for 11006.

3.2. Droplet Size Classification Categories

The target droplet size spectra based on the ASABE classification standard S-572.1 for AIN were provided by the nozzle, spray pressure and air velocity combinations, which are shown in Table 5.

Table 5. Droplet size classification categories for air induction nozzles (AIN) based on the American Society of Agricultural and Biological Engineers (ASABE) classification standard S-572.1. VDM ($D_{v0.5}$) is generally used for droplet size classification.

Droplet Size Spectra	VDM ($D_{v0.5}$)	Nozzle	Spray Pressure/kPa	Air Velocity/m·s ⁻¹
Fine	226.5	11001	700	2~5
Medium	236.8~298.4	11001	400~600	2~4
	252.3~311.0	11002	400~600	2~4
	267.2~320.8	11004	400~600	2~4
	292.0~340.8	11005	500~600	2~5
	302.4~310.9	11006	500~600	2~5
Coarse	352.8~356.1	11001	300	2~4
	343.5~348.2	11002	300	2~4
	341.3~355.4	11004	300	2~4
	347.7~379.3	11005	200~300	2~5
	349.8~363.8	11006	200~300	2~5
	364.3~389.1	11008	400~500	2~5
Very Coarse	388.7~422.1	11005	200	2~5
	391.5~436.8	11006	200	2~5
Extremely Coarse	512.7~521.1	11008	200	2~5

Table 5 shows that: (1) The 11001 nozzle provided Fine droplet size spectra at 700 kPa; (2) most of the tested nozzles (except 11008) provided Medium droplet size spectra under different spray pressure and air velocity combinations; (3) all nozzles tested provided Coarse droplet size spectra with different

spray pressure and air velocity combinations; (4) nozzles 11005 and 11006 provided Very Coarse droplet size spectra at 200 kPa; (5) nozzle 11008 provided Extremely-Coarse droplet size spectra at 200 kPa. No Extremely Fine, Very Fine, or Ultra-Coarse droplet categories were observed in this study by the tested nozzles. To complete the droplet size spectra classification category for AIN, further studies should be carried out to find nozzles that provide these three droplet categories in the future.

Except for the 11005 and 11006 nozzles, the nozzles were observed to have a single droplet category at 400 kPa, 500 kPa and 600 kPa, while they were observed to have different droplet categories at 200 kPa, 300 kPa and 400 kPa. The 11005 and 11006 nozzles were observed to provide Coarse droplet size spectra at 200 kPa, 300 kPa and 400 kPa, and provided Medium droplet size spectra at 500 kPa and 600 kPa. These results revealed that, for a given nozzle, the decrease rates of droplet sizes decreased with the increasing spray pressure, which is consistent with the previous analysis in Section 3.1. However, the reason why the 11005 and 11006 nozzles had exceptional results compared with other nozzles is not yet clear.

For a given nozzle and spray pressure, a single droplet category was observed at air velocities of 3 m/s and 4 m/s, and this result was adapted to all tested nozzles in this study. For the 11001, 11002 and 11004 nozzles at 300 kPa, 11005 and 11006 nozzles at 400 kPa and 11008 nozzle at 600 kPa, the droplet category was observed as Coarse at 2 m/s, 3 m/s and 4 m/s and observed as Medium at 5 m/s. These results are consistent with the results in Section 3.1, which showed that compared with air velocities of 3 m/s and 4 m/s, an air velocity of 5 m/s could result in the secondary breakup of droplets and furthermore result in a reported smaller droplet category.

Based on the observations in this study, some suggestions are proposed both for wind tunnel and field studies to improve the accuracy of the results in AINs and other spray examinations: (1) The solution temperature should be strictly controlled in spray tests, or ANCOVA should be conducted after spray tests to eliminate the influence of DST on spray test results if it is not possible to control the solution temperature; (2) air velocities of 2 m/s and 5 m/s are not appropriate for spray tests. The 2 m/s velocity resulted in the suspension of small droplets, and the 5 m/s velocity resulted in the drift of small droplets and secondary breakup of large droplets. This study was carried out at the temperature range of 22~31 °C, and the DST range was 70.56~72.32 dyn/cm with a variation of 1.76 dyn/cm. However, more studies should be carried out at other temperatures to determine the smallest variation in temperature and DST, which would influence the spray test results.

4. Conclusions

The aims of this study were to understand the influences of spray pressure, air velocity and nozzle orifice diameter size on droplet characteristics and to determine the droplet classification categories for AINs. Different results regarding the influence of spray parameters on droplet characteristics were observed before and after ANCOVA. The results are as follows:

- (1) (a) Before and after ANCOVA, the values of $D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$ and % < 150 μm were observed to be significantly different, while the values of RS and CV were observed to be not significantly different. (b) Before ANCOVA, nozzle orifice size and spray pressure were observed to have highly significant influences on $D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$ and % < 150 μm and have no significant influences on RS and CV. Air velocity was not observed to have a significant influence on any of the droplet characteristics. After ANCOVA, spray pressure, air velocity and nozzle orifice size were observed to have significant influences on $D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$ and % < 150 μm , and to have no significant influences on RS and CV.
- (2) For a nozzle at a given air velocity, (a) the droplet size decreased with the increase of spray pressure, (b) the reduction rate of the droplet diameter size decreased with increasing spray pressure.
- (3) For a nozzle at a given spray pressure, (a) air velocities of 2 m/s and 5 m/s resulted in smaller droplets reports compared with air velocities of 3 m/s and 4 m/s, (b) $D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$ and % < 150 μm at air velocities of 3 m/s and 4 m/s were negligible and (c) air velocities of 3 m/s and 4 m/s are more suitable for agricultural spraying.

- (4) For a given spray pressure and air velocity, a larger nozzle orifice diameter not always result in larger droplet size nor lower proportion of small droplets. For example, the droplet size of 11002 was smaller than the droplet size of 11001, and the droplet size was very similar for 11005 and 11006.
- (5) Fine, Medium, Coarse, Very Coarse and Extremely Coarse droplet classification categories, which are equivalent to the droplet size summary statistics from ASABE S-572.1, were determined to classify AINs.

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Abbreviations

Nomenclature

% < 150 μm	The proportion of spray volume contained in droplets with a diameter below 150 μm , %
AIN	Air induction nozzle
ANOVA	Analysis of variance
ANCOVA	Analysis of covariance
ASABE	American Society of Agricultural and Biological Engineers
CV	Coefficient variance
$D_{v0.1}$ and $D_{v0.9}$	Volume diameter below which smaller droplets constitute, respectively, 10% and 90% of the total volume, μm
$D_{v0.5}$	Volume median diameter (VMD) below which smaller droplets constitute 50% of the total volume, μm
DST	Dynamic Surface Tension
F	Variance of the group mean
NS	Not significant
p-value	The probability of obtaining the observed results
*	Significant
**	Highly significant

References

1. Popp, J.; Pető, K.; Nagy, J. Pesticide productivity and food security. A review. *Agron. Sustain. Dev.* **2013**, *33*, 243–255. [[CrossRef](#)]
2. Travis, J.W. Effect of Canopy Density on Pesticide Deposition and Distribution in Apple Trees. *Plant Disease* **1987**, *71*, 613–615. [[CrossRef](#)]
3. Patel, M.K.; Praveen, B.; Sahoo, H.K.; Sahoo, H.K.; Patel, B.; Kumar, A.; Singh, M.; Nayak, M.K.; Rajan, P. An advance air-induced air-assisted electrostatic nozzle with enhanced performance. *Comput. Electron. Agric.* **2017**, *127*, 280–288. [[CrossRef](#)]
4. Balsari, P.; Grella, M.; Marucco, P.; Matta, F.; Miranda-Fuentes, A. Assessing the influence of air speed and liquid flow rate on the droplet size and homogeneity in pneumatic spraying. *Pest Manag. Sci.* **2018**, *75*, 366–379. [[CrossRef](#)] [[PubMed](#)]

5. Petit, J.; Méjean, S.; Accart, P.; Galet, L.; Schuck, P.; Le Floch-Fouéré, C.; Delaplace, G.; Jeantet, R. A dimensional analysis approach for modelling the size of droplets formed by bi-fluid atomisation. *J. Food Eng.* **2015**, *149*, 237–247. [[CrossRef](#)]
6. Douzals, J.; Heidary, M.H. How spray characteristics and orientation may influence spray drift in a wind tunnel. *Asp. Appl. Biol. Biol.* **2014**, *122*, 271–278.
7. Creech, C.F.; Henry, R.S.; Fritz, B.K.; Kruger, G.R. Influence of herbicide active ingredient, nozzle type, orifice size, spray pressure, and carrier volume rate on spray droplet size characteristics. *Weed Technol.* **2015**, *29*, 298–310. [[CrossRef](#)]
8. Yates, W.E.; Cowden, R.E.; Akesson, N.B. Nozzle design influence on uniformity of droplet size spectrums from agricultural aircraft. *Trans. ASAE* **1983**, *26*, 1633–1637. [[CrossRef](#)]
9. Butts, T.R.; Luck, J.D.; Fritz, B.K.; Hoffmann, C.W.; Kruger, G.R. Evaluation of spray pattern uniformity using three unique analyses as impacted by nozzle, pressure, and pulse-width modulation duty cycle. *Pest Manag. Sci.* **2019**, *75*, 1875–1886. [[CrossRef](#)]
10. Tang, Q.; Chen, L.P.; Zhang, R.R.; Xu, M.; Xu, G.; Yi, T.C. Droplet spectra and high-speed wind tunnel evaluation of air induction nozzles. *Front. Agric. Sci. Eng.* **2018**, *5*, 54–66. [[CrossRef](#)]
11. Rosen, M.J. Dynamic surface tension of aqueous surfactant solutions. *J. Colloid Interface Sci.* **1990**, *139*, 397–407. [[CrossRef](#)]
12. Zhao, H.; Song, J.L.; Zeng, A.J.; He, X.K. Correlations between dynamic surface tension and droplet diameter. *Trans. Chin. Soc. Agric. Mach.* **2009**, *40*, 74–79.
13. Ren, W.H.; Lin, Z.Q.; Peng, D.L. On the relationship between the liquid surface tension and the temperature and the concentration. *J. Hunan Agric. Univ. (Nat. Sci.)* **2004**, *30*, 77–79.
14. Vega, C.; Miguel, E.D. Surface tension of the most popular models of water by using the test-area simulation method. *J. Chem. Phys.* **2007**, *126*, 1–10. [[CrossRef](#)] [[PubMed](#)]
15. Hoffmann, W.C.; Fritz, B.K.; Bagley, W.E.; Lan, Y.; Devisetty, B.; Dean, S.W. Effects of air speed and liquid temperature on droplet size. *J. ASTM Int.* **2011**, *8*, 1–9. [[CrossRef](#)]
16. Miller, P.; Tuck, C.R. Factors influencing the performance of spray delivery systems: A review of recent developments. *J. ASTM Int.* **2005**, *2*, 13. [[CrossRef](#)]
17. Bai, G.; Nakano, K.; Mizukami, T.; Miyahara, S.; Ohashi, S.; Kubota, Y.; Takizawa, K.; Yan, H. Characteristics and classification of Japanese nozzles based on relative spray drift potential. *Crop Prot.* **2013**, *46*, 88–93. [[CrossRef](#)]
18. ASAE. *American Society of Engineers Spray Nozzle Classification by Droplet Spectra*; Standard 572.1; American Society of Agricultural and Biological Engineers: Saint Joseph, MI, USA, 2009.
19. De Schamphellerie, M.; Spanoghe, P.; Nuytens, D.; Caetens, K.; Cornelis, W.; Gabriels, D.; Van der Meeren, P. Classification of spray nozzles based on droplet size distributions and wind tunnel tests. *Commun. Agric. Appl. Biol. Sci.* **2006**, *71*, 201–207.
20. Czaczyk, Z.; Kruger, G.; Hewitt, A. Droplet size classification of air induction flat fan nozzles. *J. Plant Prot. Res.* **2012**, *52*, 415–420. [[CrossRef](#)]
21. Hirleman, E.D.; Felton, P.G.; Kennedy, J. *Standard Test Method for Calibration Verification of Laser Diffraction Droplet Sizing Instruments using Photomask Reticles*; ASTM Research Report E-29-1000; American Society for Testing and Materials: Philadelphia, PA, USA, 1991.
22. Nuytens, D. *Drift from Field Crop Sprayers: The Influence of Spray Application Technology Determined Using Indirect and Direct Drift assessment Means*; Katholieke Universiteit Leuven: Brussels, Belgium, 2007.
23. Hewitt, A.J. Droplet size spectra classification categories in aerial application scenarios. *Crop Prot.* **2008**, *27*, 1284–1288. [[CrossRef](#)]
24. Ferguson, J.C. *Towards the Optimisation of Coarse Sprays to Reduce Drift and Improve Efficacy in Australian Cropping Systems*; The University of Queensland: Brisbane, Australia, 2016.
25. ISO. *Equipment for Crop Protection-Sprayer Nozzles-Colour Coding for Identification*; International Organization for Standardization ISO 10625; International Organization for Standardization: Geneva, Switzerland, 2004.
26. ISO. *Equipment for Crop Protection-Methods for the Laboratory Measurement of Spray Drift-Wind Tunnels*; International Organization for Standardization ISO 22856; International Organization for Standardization: Geneva, Switzerland, 2008.
27. Eissa, M.A.; Haiying, Z.; Yu, X. Mean-square stability of split-step theta milstein methods for stochastic differential equations. *Math. Probl. Eng.* **2018**, *2018*, 1–13. [[CrossRef](#)]

28. Xu, N.; Veessler, D.; Doerschuk, P.C.; Johnson, J.E. Allosteric effects in bacteriophage HK97 procapsids revealed directly from covariance analysis of cryo EM data. *J. Struct. Biol.* **2018**, *202*, 129–141. [[CrossRef](#)] [[PubMed](#)]
29. Ferguson, J.C.; Hewitt, A.J.; O'Donnell, C.C. Pressure, droplet size classification, and nozzle arrangement effects on coverage and droplet number density using air-inclusion dual fan nozzles for pesticide applications. *Crop Prot.* **2016**, *89*, 231–238. [[CrossRef](#)]
30. Fritz, B.K.; Hoffmann, W.C. Measuring spray droplet size from agricultural nozzles using laser diffraction. *J. Vis. Exp.* **2016**, *115*, 1–7. [[CrossRef](#)] [[PubMed](#)]
31. McGinty, J.A.; Baumann, P.A.; Hoffmann, W.C.; Fritz, B.K. Evaluation of the spray droplet size spectra of drift-reducing agricultural spray nozzle designs. *Am. J. Exp. Agric.* **2016**, *11*, 1–5. [[CrossRef](#)]
32. Szakáll, M.; Isabel, U. Wind tunnel study on the size distribution of droplets after collision induced breakup of levitating water drops. *Atmos. Res.* **2018**, *213*, 51–56. [[CrossRef](#)]

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