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SPECTRUM AND VELOCITY OF DROPLETS OF SPRAY NOZZLES WITH AND WITHOUT AIR INDUCTION

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KEYWORDS

spray drift , droplet size, application technology of pesticides.

ABSTRACT

The aim of this study was to evaluate the spectrum and the velocity of droplets produced by nozzles with and without air induction, under different pressures and flow rates. The experiment was conducted in a completely randomized design with five replications, in a factorial 2 x 3 x 3 (two spray nozzles, three flow rates and three operating pressures). The spray nozzles with and without air induction of the Hypro manufacturer (GA and VP) were evaluated, with nominal flow rates of 0.76; 1.14 and 1.51 L min^{-1} and pressures of 200, 300 and 400 kPa. The spectrum and velocity of the droplets were determined directly, using a Visisize Portable P15 (Oxford Lasers, Imaging Division). The pressure increases further reduction of the VMD and the relative amplitude, and increases the droplet velocity. The droplets generated by the spray nozzles with air induction showed on average amplitude 1.54 times higher than the droplets generated by spray nozzles without air induction. The droplet velocity showed little variation between the nozzles with and without air induction with the same pressure and flow rate, however, spray nozzles with larger flow rates and pressures produced droplets with higher velocities.

INTRODUCTION

The use of air induction nozzles is a commonly used method as a drift reduction strategy in the application of crop protection products. Several studies using these nozzles types indicate reduction of drift percentage in relation to nozzles without air induction (Bueno et al., 2013; Silva et al., 2014a; Silva et al., 2016). The mechanism at these nozzles follows the operating principle of a Venturi tube. These stand out from the other spray nozzle types because the flow rate of liquid and air are mixed inside a chamber, when passing under high pressure by the nozzle and coming into contact with the atmosphere, it forms droplets with air bubbles inside (Mota & Antuniassi, 2013; Leite & Serra, 2013; Silva et al., 2014b).

These nozzles with air induction reduce the drift problem because they generally produce droplets larger than the droplets usually produced by similar nozzles without induction, and many of these droplets contain one or more air bubbles (Matthews, 2000). Chechetto et al. (2013), in an experiment evaluating the influence of spray nozzles and adjuvants on the potential of wind drift reduction, found that the lowest values of drift percentage were obtained with the nozzles with air induction in all treatments, in comparison with pre-orifice nozzles.

However, air bubbles inside the droplet interfere with its transport and deposition pattern. Faggion (2008) stated that the velocity of the droplets is lower for the air induction nozzles than the conventional ones. The velocity increases with the decrease of the air captured percentage. According to the author, this result is expected because the presence of air inside the droplets increases their diameter and decreases their density; consequently the velocity of displacement reduces by the resistance force to the passage offered by the air.

Although, Nuyttens et al. (2009) showed that air induction nozzles produce droplets with higher velocities for the same nominal flow rate and operating pressure, they produce slower droplets of the same size, demonstrating that the size effect overlaps the ejection velocity effect of the droplet. According to the authors, droplets of larger size are generally associated with higher fall rates. In addition, by increasing the operating pressure at most nozzles, the droplets will be finer and with higher velocity. As the droplet reduction effect is predominant, the risk of drift increases. However, for some nozzles, as shown by Miller & Smith (1997), the increase in pressure

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does not increase the drift risk, since there is a predominance of the drop velocity effect.

Therefore, the movement mechanism of a droplet after its launch by the nozzles is complex, confirming the necessity of more accurate studies, since this information can be useful for the understanding of the spray penetration in the plant canopy and of the drift risk.

Most of the equipment for evaluating droplet size in real time is based on the laser diffraction technique; however, this technique may present accuracy problems when used with liquids of different physicochemical composition (Murphy et al, 2004). In addition, many are unable to measure the droplets velocity. So, a great deal of interest has arisen in the equipment of image analysis, which do not present the problems mentioned for the laser beam diffraction equipment (Kashdan et al., 2007).

Wang et al. (2015), studying the performance of spray nozzles by image analysis, stated that the relation between droplet size and velocity still needs more scientific studies for their understanding. Sayinci (2015) also showed that this relation is unclear and attribute this to high velocity variation for droplets of the same size in a spray jet.

Thus, the aim of this study was to evaluate the spectrum and the velocity of droplets produced by nozzles with and without air induction of the same manufacturer submitted to different operating pressures and flow rates.

MATERIAL AND METHODS

The experiment was carried out at the Machinery and Agricultural and Forestry Tires Test Center (NEMPA) at the Lageado Experimental Farm of the School of Agronomy - FCA/UNESP, in Botucatu – SP, Brazil.

The spectrum and the velocity of droplets generated by different spray nozzles with and without air induction were evaluated under different operating conditions. The spray nozzles used in the experiment are described in Table 1.

TABLE 1. Spray nozzles used in the tests.

Manufacture	Model	Flow rate (L min^{-1})	Characteristic
Hypro	VP 110-02	0.76	Without air induction
	VP 110-03	1.14	
	VP 110-04	1.52	
	GA 110-02	0.76	With air induction
	GA 110-03	1.14	
	GA 110-03	1.52	

The experiment was conducted in a completely randomized design, with five replications, in the 2 x 3 x 3 factorial scheme (two spray nozzle models, three flow rates and three operating pressures). Each replicate consisted of one spray nozzle where five equal spray nozzles were used to mount the five replicates. Spray nozzles with and without air induction were evaluated, with nominal flow rates of 0.76; 1.14 and 1.51 L min^{-1} and at pressures of 200, 300 and 400 kPa.

In order to reduce the surface tension of the spray to levels closer to those used in the field, Agral's adjuvant from Syngenta was added, characterized as adhesive spreader of the Nonil Fenoxi Poli Ethanol chemical group. The surface tension of the water at 25°C was 72 mN m^{-1}, and after the adjuvant addition at the concentration of 0.05% v v^{-1}, it was reduced to 32 mN m^{-1}. All tests were performed with the same spray type.

The spraying was evaluated by taking into account the spectrum and velocity of droplets produced by the nozzles under different operating conditions. The following parameters were obtained: Dv0.5 (droplet diameter such that 50% of the volume of the sprayed liquid consists of droplets of size smaller than this value, also known as volume median diameter- VMD), droplet velocity and relative amplitude (RA).

The determinations were performed directly, using a real-time droplet analyzer based on high resolution image analysis. The VisiSize Portable P15 image particle analyzer was used (Oxford Lasers, Imaging Division, Oxford, U.K.). For this method, the characterization is carried out in real time by Visisize Particle Sizing software, developed by the same equipment manufacturer. The system analyzes the droplet spectrum using a technique called Particle/Droplet Image Analysis (PDIA) (Carvalho et al., 2017). The system is capable of measuring droplets with diameter above 5 µm. In addition to measuring the particle diameter distribution, the equipment provides the velocity of the particles in real time. To provide the average of the spray parameters, the system was programmed to count ten thousand droplets in each repetition.

Prior to the performance of each test, in the VisiSize Portable P15 image particle analyzer, a calibration was performed using a spray nozzle from the TeeJet, XR8003 model and a spray containing only water, which produces droplets with VMD around 150 µm.

In the determination of the droplet spectrum, a spray equipment was assembled so that all the sprayed jet passed transversely through the light beam of the analyzer, allowing the direct average droplet spectrum to be obtained directly for each desired condition. The spray nozzle was located 50 cm above the optical beam (ASAE, 2000).

The tests were carried out in a controlled environment in order to minimize the effect of environmental conditions (air temperature below 28°C, relative air humidity above 60% and absence of winds).

All data were first submitted to the residues normality tests of the Shapiro-Wilk and Kolmogorov-Smirnov and the variances homogeneity of Levene, both at 0.01 of significance, with the SPSS 20 program (SPSS, 2013). In cases where the assumptions were not met, the data were transformed into $\sqrt{x}$ and submitted to the new analysis. Only when the transformation corrected at least one of the assumptions, without harming the others, the transformed data were used for analysis of variance. Otherwise, the original data were used.

In all experiments, after the analysis of the assumptions, the data were submitted to analysis of variance by the SISVAR 5.3 statistical program (Ferreira, 2008). When relevant, the treatments were compared by Tukey test, at 0.05 significance.

RESULTS AND DISCUSSION

The F values calculated in the data analyzes of variance are shown in Table 2. As the tests were conducted in the laboratory, the coefficients of variation obtained in the experiment presented low values, varying from 3.40% for the RA until 7.88% for the average droplet velocity. The triple interaction was significant for VMD and RA, but this did not occur for the average droplet velocity.

TABLE 2. Summary of the variance analysis table of the data related to the volume median diameter (VMD), relative amplitude (RA) and droplet velocity, resulting from application with spray nozzles with and without air induction, with different flow rates and operating pressures.

Source of variation	Calculated F value		
	VMD	RA	Velocity
Nozzle	3811.202**	3562.219**	0.000^{ns}
Flow rate	170.030**	39.007**	186.624**
Pressure	703.680**	382.762**	48.472**
Nozzle x Flow rate	91.242**	39.996**	5.843**
Nozzle x Pressure	333.119**	75.754**	0.883^{ns}
Flow rate x Pressure	63.253**	36.938**	2.747*
Nozzle x Flow rate x Pressure	39.494**	15.506**	0.613^{ns}
C.V. (%)	3.69	3.40	7.88

C.V.: Coefficient of variation; * significant at 0.05; ** significant at 0.01, ^{ns} not significant at 0.05.

The spray nozzles with air induction produced droplets with higher VMD than the spray nozzles without air induction (Table 3), at all operating pressures and nominal flow rates, which are less prone to drift losses. The existence of the Venturi system attached to the pre-orifice leads to the increase of the droplets size in function of the air mixture to the droplets. This behavior is already known (Mcginty et al., 2016); however, the magnitude of the increase in the droplet size due to the different geometries of construction is not known.

The nozzles without air induction provided lower RA values than the nozzles with air induction at all operating pressures and rated flow rates. This result may have been due to the fact that the mixture of air and liquid inside the nozzle with air induction chamber causes to each droplet to have a different amount of air inside it, corroborating for greater variation in its diameter. The higher the RA is, the greater will be the variation of spray droplet sizes, and a homogeneous droplet spectrum has RA value tending to zero. The higher the relative amplitude value is the larger will be the droplet size range (Cunha et al., 2016). The spray nozzles with air induction, although they produced droplets of larger diameters, presented a greater variation of diameter than the droplets generated by the nozzles without air induction.

TABLE 3. Volume median diameter (VMD) and relative amplitude (RA) resulting from the application of spray nozzles with (GA) and without (VP) air induction, with different flow rates and operating pressures.

Flow rate (L min^{-1})	Pressure (kPa)	VMD (µm)	
		Nozzle	
		VP	GA
0.76	200	153.74 b	277.86 a
	300	142.46 b	228.74 a
	400	134.42 b	203.00 a
1.14	200	142.48 b	241.84 a
	300	134.06 b	184.66 a
	400	128.58 b	168.56 a
1.52	200	158.82 b	355.32 a
	300	138.76 b	224.42 a
	400	130.72 b	179.90 a
C.V./ F_{LEVENE}/ K-S		3.69/4.211/**0.079**	
		RA	
		Nozzle	
Flow rate (L min^{-1})	Pressure (kPa)	VP	GA
0.76	200	1.05 a	1.55 b
	300	0.96 a	1.63 b
	400	0.92 a	1.42 b
1.14	200	1.11 a	1.87 b
	300	0.92 a	1.64 b
	400	0.88 a	1.24 b
1.52	200	1.11 a	1.62 b
	300	0.93 a	1.41 b
	400	0.88 a	1.15 b
C.V./ F_{LEVENE}/ K-S		3.40/**2.208**/**0.100**	

Averages followed by lower case letters in the lines differ from each other by the Tukey test at the 0.05 level of significance. F_{Levene}, K-S: statistics of the Levene and Kolmogorov-Smirnov tests, respectively; values in bold indicate residues with normal distribution and homogeneous variances at 0.01 of significance. CV (%): coefficient of variation.

Table 4 shows the results obtained from VMD and RA for the unfolding of the interaction between pressure and flow rate.

TABLE 4. Volume median diameter (VMD) and relative amplitude (RA) resulting from the application with spray nozzles (GA) and without (VP) air induction, with different flow rates and operating pressures.

		VMD (µm)		
		Flow rate (L min^{-1})		
Nozzle	Pressure (kPa)	0.76	1.14	1.52
GA	200	277.86 b A	241.84 c A	355.32 a A
	300	228.74 a B	184.66 b B	224.42 a B
	400	203.00 a C	168.56 c C	179.90 b C
VP	200	153.74 a A	142.48 b A	158.82 a A
	300	142.46 a B	134.06 a AB	138.76 a B
	400	134.42 a B	128.58 a B	130.72 a B
C.V./F_{LEVENE}/K-S		3.69/4.211/**0.079**		

		RA		
		Flow rate (L min^{-1})		
Nozzle	Pressure (kPa)	0.76	1.14	1.52
GA	200	1.55 a B	1.87 c C	1.62 b C
	300	1.63 b C	1.64 b B	1.41 a B
	400	1.42 c A	1.24 b A	1.15 a A
VP	200	1.05 a B	1.11 a B	1.11 a B
	300	0.96 a A	0.92 a A	0.93 a A
	400	0.92 a A	0.88 a A	0.88 a A
C.V./F_{LEVENE}/K-S		3.40/**2.208**/**0.100**		

Averages followed by distinct letters, lowercase in the row and upper case in the column, differ from each other by the Tukey test at the 0.05 level of significance. F_{Levene}, K-S: statistics of the Levene and Kolmogorov-Smirnov tests, respectively; values in bold indicate residues with normal distribution and homogeneous variances at 0.01 of significance. CV (%): coefficient of variation.

At the nozzles with air induction and pressure of 200 kPa, the highest VMD was obtained with a flow rate of 1.52 L min^{-1}. When the pressure was raised to 300 kPa, no statistical difference was observed between the VMD of the spray nozzles with air induction and flow rate of 0.76 and 1.52 L min^{-1}, which were higher than the VMD of the nozzle with flow rate of 1.14 L min^{-1} (184.66 µm). The highest VMD at the pressure of 400 kPa was obtained at the nozzle with flow rate of 0.76 L min^{-1} (203 µm). With this, there was an inversion of the VMD results between spray nozzles with flow rates of 0.76 and 1.52 L min^{-1} when the pressure increased from 200 to 400 kPa. The VMD of the nozzle with air induction and flow rate of 1.14 L min^{-1} was lower than the other flow rates evaluated. In general, a linear relation is expected, in which the increase of the flow rate leads to the increase of the VMD, due to the increase of the outlet orifice. However, this relation, especially at the nozzle with air induction, can be altered by the existence of a pre-orifice controlling the flow rate and the outlet orifice, which controls the droplet size. Etheridge et al. (1999) also found unexpected results of this nature. The authors attributed this to the internally generated turbulence at the nozzle with air induction.

The nozzles without air induction at 200 kPa pressure with a flow rate of 0.76 and 1.52 L min^{-1} showed no statistical difference between the VMD, but these were higher than the VMD of the nozzle with flow rate of 1.14 L min^{-1}. When submitted to pressures of 300 and 400 kPa, there was no difference for the VMD among the different flow rates. With this, the increase of the pressure reduces the VMD variation of the nozzles without air induction, even of different flow rates.

The spray nozzles with air induction and flow rate of 0.76 L min^{-1} presented lower RA when subjected to a pressure of 200 kPa (1.55). However, when the pressure was raised to 300 and 400 kPa, the lowest RA values were obtained with the nozzles with flow rate of 1.52 L min^{-1}. Cunha et al. (2007) verified that the increase in pressure corroborates for larger RA. In the same study, when using the ADI 110-02 low drift nozzles, the lowest RA values were found at a pressure of 200 kPa (1.00), while at a pressure of 400 kPa the RA was 1.27.

The RA values of the spray nozzles without air induction did not present significant differences among the flow rates. However, when the nozzles without air induction were subjected to a pressure of 200 kPa, the highest values of RA were observed. This relation is possibly due to the very constructive geometry of this high advanced model.

The droplet velocity was equal between the spray nozzles with and without air induction for the flow rates of 0.76 and 1.52 L min^{-1} (Table 5). However, the spray nozzles without air induction with a flow rate of 1.14 L min^{-1} presented higher droplets velocity (2.74 m s^{-1}) than the nozzles with air induction and with the same flow rate (2.55 m s^{-1}). Faggion (2008) stated that the droplet velocity is lower for the nozzles with air induction than the conventional ones, but this was not observed at all flow rates. Nuyttens et al. (2009) affirmed that the droplets velocity is linked to their size and that droplets of larger diameters lead to higher velocities.

TABLE 5. Droplet velocity (m s^{-1}) resulting from the application with spray nozzles with (GA) and without (VP) air induction, with different flow rates.

	Velocity (m s^{-1})	
	Nozzle	
Flow rate (L min^{-1})	VP	GA
0.76	1.88 a B	1.94 a C
1.14	2.74 a A	2.55 b B
1.52	2.76 a A	2.86 a A
C.V./ F$_{LEVENE}$/ K-S	7.880/3.342/0.137	

Averages followed by distinct letters, lowercase in the row and upper case in the column, differ from each other by the Tukey test at the 0.05 level of significance. F$_{Levene,}$ K-S: statistics of the Levene and Kolmogorov-Smirnov tests, respectively; values in bold indicate residues with normal distribution and homogeneous variances at 0.01 of significance. CV (%): coefficient of variation.

This difference can be explained by the fact that the velocity is not only related to the droplet size, but also to the kinetic energy of the droplet launch and its density. Depending on the operating conditions, one of these factors may be more pronounced than the other, leading to a behavior variation as found in this operation. Droplets produced by the nozzles with air induction are larger; however, its nozzle ejection speed may be lower, given the pressure fall promoted by the turbulence chamber responsible for mixing the air and the liquid. Although, after their ejection, they suffer less reduction in fall velocity than the droplets produced by nozzles without air induction. This can be explained by the fact that smaller droplets, which have lower mass, tend to have their velocity reduced by the action of wind resistance in the path between their release and the target.

Nozzles with and without air induction with higher flow rates produced droplets with higher velocities. In a study conducted by Nuyttens et al. (2009), using spray nozzles with and without air induction, with flow rates of 0.76; 1.14; 1.52 and 2.27 L min^{-1}, also verified that the droplets generated by nozzles with higher flow rates presented higher velocities. The authors attributed this mainly to the larger droplet diameter generated at the nozzles of higher flow rate.

Spray nozzles with higher flow rates produced droplets with higher velocities (Table 6), except for the pressure of 200 kPa, where the droplet velocities were statistically the same for the nozzles with flow rates of 1.14 L min^{-1} and 1.52 L min^{-1} (2.42 and 2.43 m s^{-1}, respectively). Nozzles with higher flow rates have a larger outlet orifice, which promotes less restriction to the passage of the liquid, possibly contributing to the increase in droplet velocity.

TABLE 6. Droplet velocity (m s^{-1}) resulting from the application with spray nozzles with different flow rates and at different operating pressures.

	Velocity (m s^{-1})		
	Flow rate (L min^{-1})		
Pressure (kPa)	0.76	1.14	1.52
200	1.73 b B	2.42 a B	2.43 a C
300	1.93 c AB	2.69 b A	2.90 a B
400	2.07 c A	2.83 b A	3.13 a A
C.V./F$_{LEVENE}$/K-S	7.880/3.342/0.137		

Averages followed by distinct letters, lowercase in the row and upper case in the column, differ from each other by the Tukey test at the 0.05 level of significance. F$_{Levene,}$ K-S: statistics of the Levene and Kolmogorov-Smirnov tests, respectively; values in bold indicate residues with normal distribution and homogeneous variances at 0.01 of significance. CV (%): coefficient of variation.

The increases in pressure caused a raise in the droplets velocity at all flow rates. At 1.52 L min^{-1}, the highest velocity was obtained at a pressure of 400 kPa (3.13 m s^{-1}). Kun et al. (2015) and Miller & Smith (1997) found similar results, they found that the increase in pressure caused a raise in droplet velocity. Also Nuyttens et al. (2009), using standard flat spray nozzles with flow rates of 1.14 L min^{-1} under different pressures, found a 25.8% increase in droplet velocity when the pressure was raised from 200 to 400 kPa.

The increase of the pressure raises the kinetic energy of the droplets, resulting in increased velocity. Higher velocities cause the path between the moment of the droplet launch and the target to be traveled in a shorter time, contributing to drift reduction (Ozkan, 1998). However, as pressure increases, VMD reduction also occurs, interfering inversely with the drift. Therefore, it is clear that only the increase in operating pressure is not a totally viable alternative when reducing drift in crop protection products applications.

It should be noted that in this work the droplet velocity was calculated for the average for each nozzle. Different analysis can be done by considering the velocity for each class of droplet size for each nozzle, which would allow an understanding of the difference between them in each class of droplet size.

CONCLUSIONS

The spray nozzles with air induction produced droplets with larger VMD than corresponding nozzles without air induction. This increase is 63.31%.

The increases of the pressure provided VMD and RA reduction and increased average droplet velocity.

Nozzles with air induction promoted a less homogeneous droplet spectrum than the nozzles without air induction.

The droplet velocity showed little variation between nozzles with and without air induction with the same flow rate and pressure; however, nozzles with higher flow rates produced droplets with higher velocities.

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