ea engenharia agrícola

Journal of the Brazilian Association of Agricultural Engineering

ISSN: 1809-4430 (on-line)

SPECTRUM, VELOCITY AND DRIFT OF DROPLETS SPRAYED BY NOZZLES WITH AND WITHOUT AIR INDUCTION AND MINERAL OIL

Doi:http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v37n3p502-509/2017

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ABSTRACT: The aim of this study was to evaluate the spectrum, the velocity and the potential drift risk of droplets sprayed by nozzles with and without air induction, with the addition of mineral oil to the spray solution. The experiment was conducted in a completely randomized design with five replications; in a factorial model 2 x 2 (two spray nozzles and spray solution with and without mineral oil Assist®). Spray nozzles with and without air induction were evaluated, with nominal flow rate of 1.14 L min^{-1} and pressure of 300 kPa. The spectrum and the velocity of droplets were evaluated directly, using a droplet analyzer (VisiSize D30) in real time based on the analysis of high-resolution images. The drift potential was evaluated in an open circuit wind tunnel. The data were submitted to analysis of variance and comparison test. In general, the addition of mineral oil (1.5% V V^{-1}) resulted in an increase in the velocity of droplets, reduced drift and more homogeneous droplet spectrum. Air induction nozzles promoted larger and less homogeneous droplets, but they little affected the velocity of the droplets. There is an inverse correlation between drift potential and volume median diameter (VMD), which indicates that VMD can be used to predict the behavior of drift risk.

KEYWORDS: adjuvants, droplet size, application technology.

INTRODUCTION

The use of spray nozzles with air induction for applying crop protection products has grown worldwide as a strategy to reduce drift, and consequently reduction of environmental contamination risk. The drift is considered one of the biggest problems of agriculture, and it can be defined as the trajectory deviation that prevents the produced droplets to hit the target, a fact that is mainly related to the droplet size and wind speed (CHECHETTO et al., 2013; ALVES & CUNHA, 2014).

Coarse droplets are less prone to suffer wind action, and therefore they are not carried away from the application areas. In addition to reducing the environmental contamination risk, spray nozzles with air induction provide droplets with air induced in its interior in the form of air bubbles (GANDOLFO et al., 2013) due to the Venturi system, thereby reducing the droplets rebound effect when hitting the target.

In addition to the size, the droplet velocity also influences the efficiency of the application process of plant protection products. The higher the velocity is, the lower will be the risk of drift (MCGINTY et al., 2016). The droplets velocity is smaller for nozzles with air induction when compared to the conventional ones (DORR et al, 2013). However, nozzles with air induction produce droplets with higher velocity for the same nominal flow rate and pressure, though they produce slower droplets for the same size, which demonstrates that the size effect overlaps the droplet ejection velocity effect (NUYTTENS et al., 2009).

Thus, a droplet movement mechanism after its launch by the nozzle is complex, confirming the need for more accurate studies, since this information may be useful for understanding the penetration of the spray jet in the plants canopy and the drift risk.

The addition of adjuvants to the spray solution has also been an alternative adopted in most of crop protection products applications, because it promotes physicochemical changes in the spray

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Received in: 11-25-2016

Accepted in: 12-23-2016

mixture, consequently reducing the drift (GANDOLFO et al., 2013; HILZ & VERMEER, 2013). Among the many types of adjuvants available in the market, the widespread use of mineral oils is highlighted because it acts reducing the surface tension and increasing the wettability, spreading and absorption of the products (BAYER et al., 2011).They may also have drift reduction action by increasing the diameter of the spray droplets (OLIVEIRA et al., 2013).

An important tool for the study of drift quantification or drift potential risk is the wind tunnel, which simulates the wind conditions observed in the field. In addition to validating models that estimate the drift, the wind tunnel allows to select and develop application techniques that reduce the environmental and economic impact caused by the loss of crop protection products (OLIVEIRA et al., 2013).

As for the droplet size evaluation, most of the equipment is based on the laser diffraction technique. However, many devices do not have the capacity to measure the droplets velocity. Therefore, a great interest in image analysis equipment arose, because they are able to characterize the spectrum and to measure the droplets velocity (WANG et al., 2015).

There are studies in the literature that address the use of spray nozzles with air induction containing mineral oil, which address droplet spectrum and coverage of the applications, but there are few studies available that address velocity, drift potential of sprayed droplets and their correlation.

Thus, the aim of this study was to evaluate the spectrum, the velocity and the potential drift risk of droplets sprayed by nozzles with and without air induction, with the addition of mineral oil to the spray solution.

MATERIAL AND METHODS

The experiment was carried out in the Agricultural Mechanization Laboratory of the Federal University of Uberlândia and in the Machinery Testing Center and Agroforestry Tires of the São Paulo State University – Botucatu Campus.

The spectrum, the velocity and the potential drift risk of droplets by nozzles with and without air induction were analyzed, and in spray solutions with and without mineral oil. The experiment was carried out in a completely randomized design with five replications; in a factorial 2 x 2 (two spray nozzles and spray solution with and without mineral oil). Aiming to study the effect of air induction on spraying, Hypro® flat fan spray nozzles with rated flow of 1.14 L min^{-1} were evaluated at a pressure of 300 kPa: VP 110-03 (without air induction) and GA 110-03 (with air induction).

In order to reduce the surface tension of the spray solution to levels closer to those used in the field with the presence of crop protection products, the Agral® adjuvant from Syngenta® was added to all spray solutions. This product is characterized as adhesive spreader of the nonyl phenoxy poly ethanol chemical group. The surface tension of the water with temperature of 25°C (72 mN m^{-1}) was reduced to 32 mN m^{-1} after the addition of the adjuvant at the concentration of 0.05% V V^{-1}.

In the treatments with mineral oil, besides of the Agral®, the Assist® adjuvant was used, from BASF® manufacturer, from the aliphatic hydrocarbons chemical group. The product was added in the concentration of 1.5% V V^{-1}. The choice of mineral oil was due to its great use in the field, and since in many packages, mainly from fungicides, there is its recommendation.

Before the droplet spectrum evaluation, a study of the physicochemical characteristics of the spray solutions used was done. The pH, viscosity, surface tension and electrical conductivity were analyzed, repeating them five times (CUNHA & ALVES, 2009).

The spraying was evaluated taking into account the spectrum and the droplets velocity. The following parameters were taken: Dv0.5 (droplet diameter that 50% of the sprayed liquid volume consists of smaller droplets than this value, also known as volumetric median diameter - VMD), droplets velocity and relative amplitude (RA).

The determinations were carried out directly, using a real-time droplets analyzer based on high-resolution image analysis. The VisiSize D30 equipment from the Oxford Lasers Imaging Division manufacturer was used, with a capture rate of 30 frames per second and laser beam diameter of 805 nm for jet lighting.

To relate the drift with the measured parameters, the droplets drift in wind tunnel was analysed (Figure 1a) (MOREIRA JÚNIOR & ANTUNIASSI, 2010; MOTA, 2015).The wind tunnel overall dimensions are 1.00 m of length, 0.70 m of height, test section of 5.20 m of length and total length of 6.30 m. Nylon threads of 2mm of diameter were used (Figure 1b) as artificial targets to the drift collection and they were positioned horizontally and perpendicular to the wind moving direction, arranged in the form of drawers.

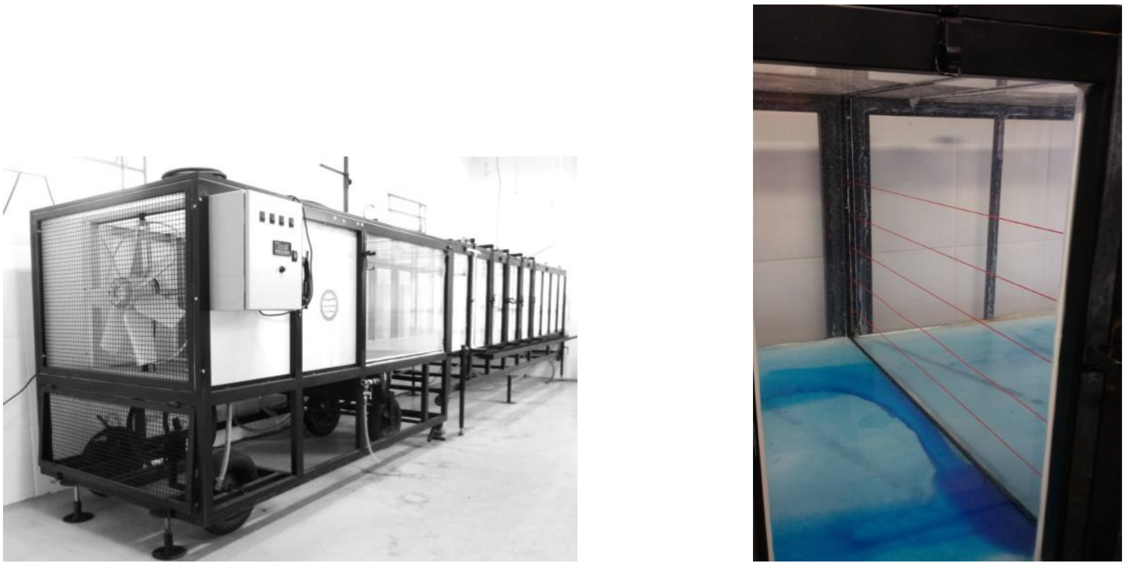

(a) (b)

FIGURE 1. Wind tunnel used in the tests (a); Distribution of nylon thread in the wind tunnel (b).

The tests were carried out with wind velocity of 2.5 m s^{-1}, which was achieved by adjusting the fan speed. For each collection, the spraying of the spray solution was carried out for 20 seconds (MOREIRA JÚNIOR & ANTUNIASSI, 2010; MOTA, 2015) in order to allow the amount of product collected from the nylon thread to be within the reading range of the spectrophotometer.

In all repetitions, the temperature and relative humidity were measured, using a portable digital hygrometer term Minipa, MTH 1362W model, positioned out of the wind tunnel, near to the fan where the air enters the tunnel. The wind speed was measured in real time, using a digital anemometer fan type (Minipa brand, MDA 11 model). The anemometer was placed inside the wind tunnel, between the air outlet and the spray nozzle.

For the formulation of spray solution, potable water at room temperature was used, and for all treatments the artificial dye (marker) for food purposes, Brilliant Blue, “Duas Rodas” manufacture, was used, at a concentration of 6000 ppm.

This dye has low toxicity and is a highly water soluble product, and it is used in several studies with satisfactory results as tracer in the respective experiments for deposition measures (CHECHETTO et al., 2013; MOREIRA JÚNIOR & ANTUNIASSI, 2010).

From the dye concentration results calculated for each sample, the calculation of the spray volume collected in each thread was made. For this, the dye concentration in the sample (mg L^{-1}) and the amount of water used for washing each thread were considered.

With the spray solutions values present in each thread, the drift rate by thread was estimated, which is the percentage of the sprayed spray solution volume retained on the thread as described in the [eq. (1)], and the total drift rate, which was the sum of the drift rate of all threads for each repetition.

$$\text{DI thread} = \frac{SV \times AT \times T \times \frac{1}{1000}}{q} \times 100 \tag{1}$$

That,

DI thread - Drift index by thread (%);

SV - spray volume collected by thread (µL);

AT - tunnel area length represented by each thread (cm);

T - Spraying time for each repetition (sec),

q - spray nozzle flow (mL min^{-1}).

All data were first submitted to Shapiro-Wilk normality test of waste and Levene homogeneity of variance, both at 0.01 of significance with the SPSS 20.0 program. After the analyze of the assumptions, the data were submitted to analysis of variance by the SISVAR 5.3 statistical program (FERREIRA, 2014).The physicochemical characteristics of the spray solution were compared by the t test, at 0.05 significance. When relevant, the treatments were compared by Tukey test, at 0.05 of significance. Additionally, the Pearson correlation analysis between the VMD and the drift rate, at the 0.05 of significance, was also carried out.

RESULTS AND DISCUSSION

The results of physicochemical analyses of the spray solutions are shown in Table 1. For the viscosity, since there was no homogeneity of the variances, the transformation of the data in x^{½} was used.

TABLE 1. Physicochemical characteristics of the spray solution.

	Spray Solution		
Characteristic	Surfactant (Agral)	Surfactant+mineral oil (Agral + Assist)	C.V./F$_{\text{LEVENE}}$/S-W
pH	5.33 a	5.36 a	2.10/**0.31**/**0.95**
Viscosity (mPa·s)	1.09 b	1.25 a	0.50/**11.00**/**0.93**
Surface tension (mN·m^{-1})	32.00 a	32.30 a	2.88/**1.92**/**0.80**
Electrical conductivity (µS·cm^{-1})	45.84 b	50.64 a	0.57/**0.09**/**0.83**

Averages followed by different letters in the line differ from each other by T test at 0.05 of significance. F$_{\text{Levene}}$, S-W: statistics of Levene and Shapiro-Wilk test, respectively; values in bold indicate homogeneity variances and residues with normal distribution at 0.01 of significance; no bold values indicate waste with non-normal distribution and heterogeneity variances. CV (%): coefficient of variation.

The addition of mineral oil (Assist) to the spray solution did not cause significant change in pH and surface tension. However, the electrical conductivity of 45.84 µS cm^{-1} obtained with the surfactant spray solution (Agral) was lower than the one obtained with the spray solution with Assist (50.64 µS cm^{-1}). The viscosity of the spray after the addition of mineral oil was increased in 14.68%, indicating that it may also influence the droplet spectrum.

The F values calculated in the analysis of variance of the data from Hypro® nozzles are shown in Table 2. There is a different behavior between the evaluated parameters and the interactions.

TABLE 2. Summary of the chart of the variance analysis of the data for the volumetric median diameter (VMD), relative amplitude (RA), droplets velocity and drift index, resulting from the application with spray nozzles with and without air induction, Hypro® manufacturer, with and without mineral oil.

Variation source	Calculated F Value			
	VMD	RA	Velocity	Drift Index
Nozzle	92.096**	243.191**	1.706^{ns}	662.486**
Spray Solution	4.458^{ns}	261.199**	7.232*	281.466**
Nozzle x Spray	3.928^{ns}	179.756**	0.004^{ns}	99.531**
C.V. (%)	8.93	5.11	8.53	11.40

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

When the spray solution only with the surfactant was used, the nozzles without air induction produced droplets with lower RA (0.92) (Table 3). Because the air induction system has the air inclusion mechanism and mixing it with the liquid spray, it can result in modification of the fluid dynamics inside the nozzle, and consequently the production of droplets spectrum with less uniformity. No significant differences were observed between the droplets RA generated by nozzles without air induction (VP) and with air induction (GA) when a spray solution with mineral oil was used. Possibly, this behavior is connected to the influence of the mineral oil in the droplets formation.

In the nozzles with air induction (GA), the addition of mineral oil provided RA 1.8 times lower than that obtained with the spray solution without mineral oil.

TABLE 3. Relative Amplitude (RA) resulting from the application of spray with flat fant nozzles from Hypro® manufacturer with (GA) and without (VP) air induction, with different types of spray.

Spray Solution	RA	
	Nozzle	
	VP	GA
Surfactant	0.92 a A	1.64 b B
Surfactant+mineral oil	0.84 a A	0.91 a A
C.V./F$_{LEVENE}$/S-W	5.11/**3.74**/0.82	

Averages followed by different letters differ, lowercase between the nozzles and uppercase between the spray solution, by Tukey test at 0.05 of significance. F$_{Levene}$, S-W: statistics of Levene and Shapiro-Wilk test, respectively; values in bold indicate homogeneity variances and residues with normal distribution at 0.01 of significance; CV (%): coefficient of variation.

In relation to the droplets size, the VMD was higher in the spray nozzles with air induction (198.26 µm) than the spray nozzles without air induction (134.49 µm) (Table 4). The increase of droplets VMD occurred due to the presence of air within the spray droplets.

TABLE 4. Volumetric median diameter (VMD, µm) resulting from the application with spray nozzles from Hypro® manufacturer, with (GA) and without (VP) air induction.

Nozzle	VMD (µm)
VP	134.49 B
GA	198,26 A
C.V./F$_{LEVENE}$/S-W	8.93/**3.69**/**0.93**

Averages followed by different letters differ from each other by Turkey test at 0.05 of significance. F$_{Levene}$, S-W: statistics of Levene and Shapiro-Wilk test, respectively; values in bold indicate homogeneity variances and residues with normal distribution at 0.01 of significance; CV (%): coefficient of variation.

The addition of mineral oil to the spray solution provided droplets with velocity 10.8% higher than that obtained with the spray only with surfactant (Table 5).The greater the droplet velocity, the smaller is the time spend between the ejection by the spray nozzle and the target to be hit, thus, less time at which the droplet is subjected to suffer drift. This result may have contributed to the behavior exhibited in the wind tunnel for the spray solution with mineral oil.

However, droplets with higher velocity may suffer a more pronounced rebound effect when reaching the surface. The rebound effect is minimized when working with air induction nozzle because any bubbles inside the spray droplet carry out a cushioning effect when the drop impacts the target.

When mineral oil was added to the spray solution, droplets with higher velocities were observed, which generally correspond to those with larger diameters (NUYTTENS et al., 2009). The authors state that the droplets decelerate as a result of air resistance, and smaller droplets decelerate more quickly when compared to larger droplets due to their smaller mass, which suffers a more severe deceleration caused by the wind.

TABLE 5. Droplets velocity (m s^{-1}) resulting from the application of spray nozzles* from Hypro® manufacturer, with different types of spray solution.

Spray Solution	Velocity (m s^{-1})
Surfactant	2.69 B
Surfactant+ Oil	2.98 A
C.V./F_{LEVENE}/S-W	8.53/**2.24**/**0.97**

Averages followed by different letters differ from each other by Turkey test at 0.05 of significance. F_{Levene}, S-W: statistics of Levene and Shapiro-Wilk test, respectively; values in bold indicate homogeneity variances and residues with normal distribution at 0.01 of significance; CV (%): coefficient of variation. *Average values for the GA 110-03 and VP 110-03 spray nozzles.

Due to the higher droplets VMD provided by the inclusion of air bubbles inside the droplets, the drift obtained with GA nozzles was less than that obtained in the VP nozzles, for both types of spray solutions (Table 6). CHECHETTO et al., (2013) evaluated the drift with multiple nozzles under different environmental conditions and working pressures, and lower values were found with the use of spray nozzles with induction air.

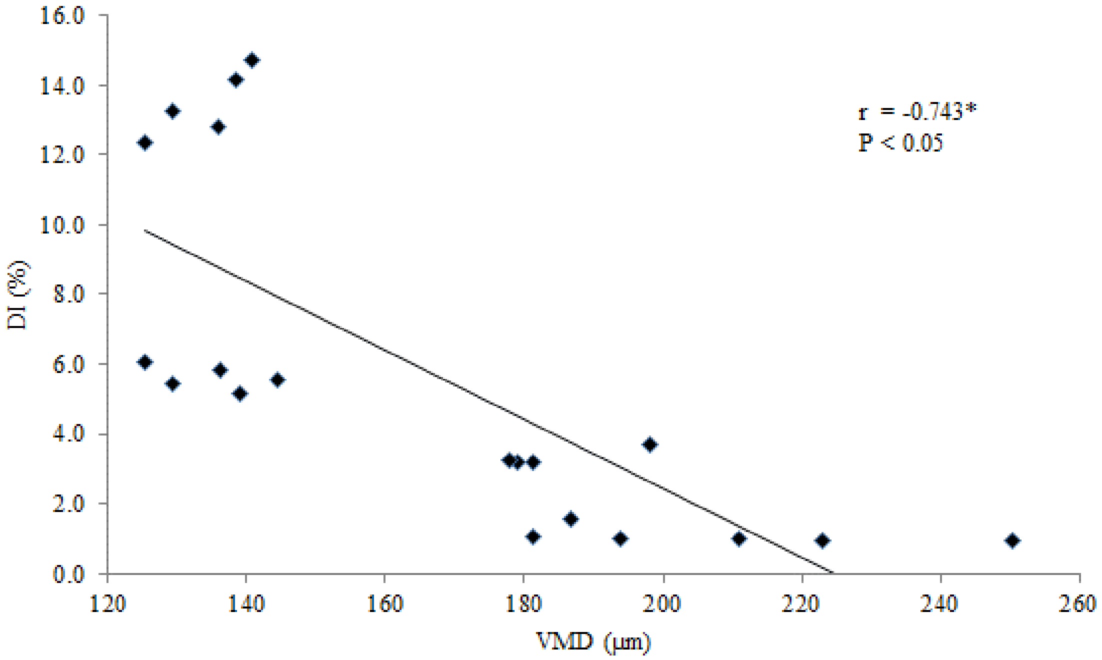
TABLE 6. Drift index (%) resulting from the application with spray nozzles from Hypro® manufacturer with (GA) and without (VP) air induction, with different types of spray.

Spray Solution	Drift Index (%)	
	Nozzle	
	VP	GA
Surfactant	13.46 b B	2.98 a B
Surfactant+mineral oil	5.61 b A	0.98 a A
C.V./F_{LEVENE}/S-W	11.40/**4.64**/**0.95**	

Averages followed by different letters differ, lowercase in line and uppercase in the column, by Tukey test at 0.05 significance. F_{Levene}, S-W: statistics of Levene and Shapiro-Wilk test, respectively; values in bold indicate homogeneity variances and residues with normal distribution at 0.01 of significance; CV (%): coefficient of variation.

The addition of mineral oil to the spray solution caused a reduction in the droplets drift, emphasizing that in the spray nozzle with air induction there was a reduction of 3.14 times and in the nozzles without air induction, the reduction was 2.4 times. Such behavior can be obtained by raising the viscosity of the spray solution. Although there was no rise in the VMD, there was possibly a reduction in the amount of fine droplets, contributing to the reduction of drift. Furthermore, the droplets velocity was increased with the presence of mineral oil, minimizing the drift (OLIVEIRA et al., 2013).

Figure 2 shows the correlation between the drift index and VMD. The drift showed a strong and inverse correlation with VMD, that is, when one parameter decreased the other increased (OLIVEIRA & ANTUNIASSI, 2012; CHECHETTO & ANTUNIASSI, 2012).



*Pearson correlation significant at the 5% of probability (P <0.05).

FIGURE 2. Correlation between the drift index (DI, %) and volumetric median diameter (VMD, µm) for the GA flat spray nozzles (with air induction) and VP (without air induction), with and without the addition of mineral oil.

With VMDs smaller than 150 µm, the highest drift indexes occurred and, consequently, there was a greater possibility of contamination of neighboring areas. This shows that the droplet size is a major factor at application moment when the aim is to reduce the drift. This behavior indicates that the characterization of drop size is a good parameter to predict the potential drift risk.

CONCLUSIONS

Air induction flat fan nozzles from Hypro® manufacturer produced droplets with greater VMD and less homogeneous droplet spectra than corresponding nozzles without air induction; however, there was no difference in droplet velocity.

In general, the addition of Assist mineral oil caused an increase in the droplets velocity, reduced drift and more homogeneous droplet spectrum.

There is an inverse correlation between drift potential and the VMD from the droplets generated, indicating that this parameter can be used to predict the behavior of the drift risk.

ACKNOWLEDGEMENTS

We thank to the CNPq, Fapemig and Capes for the financial support to conduct this research.

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