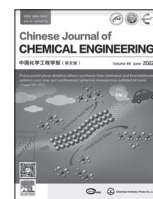




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Full Length Article

Rapid velocity reduction and drift potential assessment of off-nozzle pesticide droplets



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ABSTRACT

The droplet velocity and diameter significantly affect both the spatial drift loss and the interfacial deposition behaviors, thus determining the ultimate utilization efficiency during pesticide spraying. Investigating the spatial velocity and diameter evolutions can reveal the mechanism of drift loss and guide to design regulation strategy. Here, we explored the spatial velocity distribution of droplets after leaving the nozzle by particle image velocimetry technology and particle tracking model, considering that the effect of nozzle configuration and the air velocity. It shows that all droplets decelerate rapidly with the velocity attenuation ratio ranging from 50% to 80% within the region of 200 mm below the nozzle. The spatial velocity evolution differences between droplets in crossflow are determined by the competition of vertical drag force and net gravity, and the drag force sharply increases as the droplet diameter decreases, especially for that smaller than 150 μm . Based on the spatial evolution differences of the droplet velocity and diameter, a functional adjuvant was added to the liquid for improving the diameter distribution. And the drift loss was significantly reduced due to the reduction of the proportion of easily drifting droplets.

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1. Introduction

Spray technology that can disperse the liquid into many small droplets has been widely applied in various fields, such as spray combustion of petroleum fuels [1,2], spray coating for protecting industrial infrastructure [3], spray drying for producing powder particles [4,5], spray pesticide for agricultural protection [6], and so on. The nozzle that acts as the droplet dispersion device greatly affects the initial distribution of droplets in the primary atomization, including the diameter, velocity, atomization angle, and density [7–10]. During the pesticide spraying for pest control and plant protection, the droplet diameter and velocity can determine the kinetic energy of moving toward the target, which are generally considered as the two most important factors affecting the spatial drift and interfacial deposition behaviors and ultimately determining the utilization efficiency of pesticide [11].

The spatial diameter distribution of droplets within the spray field can be quantitatively obtained by the laser particle size ana-

lyzer, where the scattered light intensity caused by the measured droplet is related to the droplet diameter. Also, the droplet diameter can be calculated by identifying the contour profile of droplet captured by the camera with high resolution [12–14]. In the previous studies, the initial diameter distribution of droplets and its influence on the spatial drift and deposition during pesticide spraying have been extensively investigated by the wind tunnel experiment and the field test. Compared with the unsettled weather in the field, the wind tunnel assessment has excellent flexibility and controllability. American Society of Agricultural and Biological Engineers (ASABE) has adopted and perfected the classification standard of British Crop Protection Council (BCPC), and divided the droplets into very fine (<100 μm), fine (100–175 μm), medium (175–250 μm), coarse (250–375 μm), and very coarse (375–450 μm), or extremely coarse (>450 μm) [15]. The amount of drift loss is related to the proportion of very fine and fine droplets. The smaller the droplet, the longer it remains airborne and the higher possibility to be carried away by crosswind [16]. The droplet diameter distribution, as well as the spatial drift loss, is affected together by the nozzle structure, the operating pressure, and the pesticide liquid. Studies have shown that the nozzle configuration will determine the breakup pattern of the liquid sheet and then the formation mode of droplets during the primary atomization [17].

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Compared with common hydraulic nozzles, such as flat fan nozzle, hollow cone, and solid cone nozzle, air induction nozzle can produce larger droplets under the same pressure and then have the strong ability of anti-drift, which is attributed to the air inhalation that causes the bubbles to be enclosed inside the droplets [18,19]. Wang *et al.* [17] found that the hollow cone nozzle showed the strongest potential to drift, followed by the fan nozzle, and the air induction nozzle has excellent anti-drift potential in the wind tunnel test. As the nozzle size increases or the spray pressure reduces, the droplet diameter will increase and the drift loss will weaken [20–22]. Also, the diameter distribution uniformity of droplets can be improved by regulation of the liquid physicochemical properties. The addition of associative surfactant into dilute polymer solution can decrease the dynamic surface tension and shift the droplet size distribution to larger droplet sizes, substantially reducing the spray drift [23]. Chen *et al.* [24] and Lan *et al.* [25] found that the deposition and coverage on the rice were improved with the addition of plant oil adjuvants that increase the viscosity of liquid and thus reduce the number of small droplets. In all, the droplet distribution considerably relies on the atomization features of distinctive nozzles, and the correlation between them lacks definite clarification. In the field spraying, the suitable selection of nozzle and the creative modification of liquid are strongly desired to reduce the drift loss and maximize the deposition onto the target surface.

Compared with various investigations on the droplet diameter, fewer efforts have been devoted to the droplet velocity due to the greater difficulty in measuring velocity and the greater complexity in interpreting the results [18]. The commonly used technologies/instruments of measuring the droplet velocity mainly contain the phase doppler particle analyzer (PDPA), the particle image velocimetry (PIV), and the particle/droplet image analysis (PDIA). The velocity information in the PDPA experiment is obtained by calculating the frequency difference between the scattered light and the illuminated light of the moving particle, while the velocity is calculated by capturing the particle trajectory in the successive time interval during the PIV and PDIA experiments. The current research mainly focuses on the initial droplet velocity by modeling or capturing the atomization process of distinctive nozzles, including the liquid sheet formation, stretching, and breaking into droplets [26,27]. Based on energy balance, Sidahmed *et al.* [28] proposed that the initial droplet velocity was generally equal to the average liquid sheet velocity, which was examined with the experiment results from three fan nozzles by PDPA. Dorr *et al.* [18] measured the initial droplet velocity by PIV technology and found that all droplets were moving at a similar velocity at the position of droplet formation, irrespective of droplet size. Besides, the hydraulic nozzle produced the droplets with higher velocity than the air induction nozzle, agreeing well with the results of Wang *et al.* [17] and Miller *et al.* [29]. Increasing the pressure could improve the initial droplet velocity, but the addition of functional adjuvants had little effect on the droplet velocity. Nuytens *et al.* [30] plotted the cumulative droplet velocity distribution curve of several nozzles by PDPA and founded that there was a strong correlation between droplet size and velocity. In general, bigger droplet size corresponded with higher droplet velocity. However, the droplet velocity of air injection nozzles was lesser than expected, mainly because of the big pressure drop in the nozzle created by the combination of Venturi and pre-orifice effect.

Generally, the initial diameter distribution and the initial velocity distribution of spray droplets have been widely explored. However, there are few investigations on the spatial velocity and diameter evolution of droplets moving towards the target after the primary atomization is completed. The spatial velocity of droplets can not only reflect the ability to maintain their initial kinetic energy, but also provide the valuable initial conditions for droplet

spreading on the target interface that is considerably affected by the impact velocity [11,18,31–34].

Although the initial states of spray droplets may vary significantly for different typed nozzles, there should be some similarities in the spatial evolutions of droplet diameter and velocity after leaving the nozzle. Besides, the spatial evolution difference of droplets can help to improve the initial states in terms of the requirements for droplet drifting in the air or wetting on the target surface. Based on it, three representative agricultural nozzles with different configurations were selected in this paper. And the spatial velocity distributions of droplets were measured and compared by indoor PIV experiments to obtain the similarities and differences in the velocity evolution. Subsequently, the spatial velocity magnitude and direction of droplets with different sizes were numerically calculated under the crosswind to simulate the outdoor spraying application. And the differences in the droplet velocity evolution were clarified by dynamic force analysis. Then the drift potentials of spray droplets were evaluated and compared in the wind tunnel experiments before and after adding the adjuvant that can improve the diameter distribution in order to provide the theoretical guidance for nozzle selection and diameter regulation in the pesticide spraying.

2. Material and Methods

2.1. Experimental setup and method

2.1.1. Velocity measurement by PIV technology

Three commonly used and distinctive agricultural nozzles, hollow cone nozzle TR80 015, flat fan nozzle ST110 015, and air induction nozzle IDK120 015, were selected in the experiments as shown in Table 1. The sheet breakup modes of the selected nozzles during the liquid atomization are totally different. The droplets are generated by the rim breakup, wave breakup, and perforated breakup of liquid sheet respectively for the nozzle TR80 015, ST110 015, and IDK 120 015. And the liquid flow rates of the three nozzles are the same under constant pressure.

The TR nozzles usually produce fine droplets, which are suitable for the requirements of higher concentration of pesticide liquid and smaller droplets in the aerial spraying applications. Besides, most of the orchard sprayers are equipped with hollow cone nozzles. In contrast, the ST nozzles have larger spray width and produce more uniform droplets, which are widely used in the application of insecticide and fungicide spraying in the field crops. And the IDK nozzles are used in the application of herbicide spraying with larger spray volume.

Compared with the PDPA technology that can only achieve single-point measurement, the PIV technology can obtain the velocity information of droplets located in the whole region simultaneously. Fig. 1(a) shows the schematic of indoor experiment setup for droplet velocity measurement by PIV technology, which is a non-intrusive laser optical technique for the visualization of laser-illuminated flow field by tracking the movement of tracer particles in successive time intervals [35–37]. Tracer particles are

Table 1
Three distinctive agricultural nozzles in the experiments

Nozzle	Pictures	Type	Company
TR80 015		Hollow cone nozzle	Lechler GmbH
ST110 015		Flat fan nozzle	Lechler GmbH
IDK120 015		Air induction nozzle	Lechler GmbH

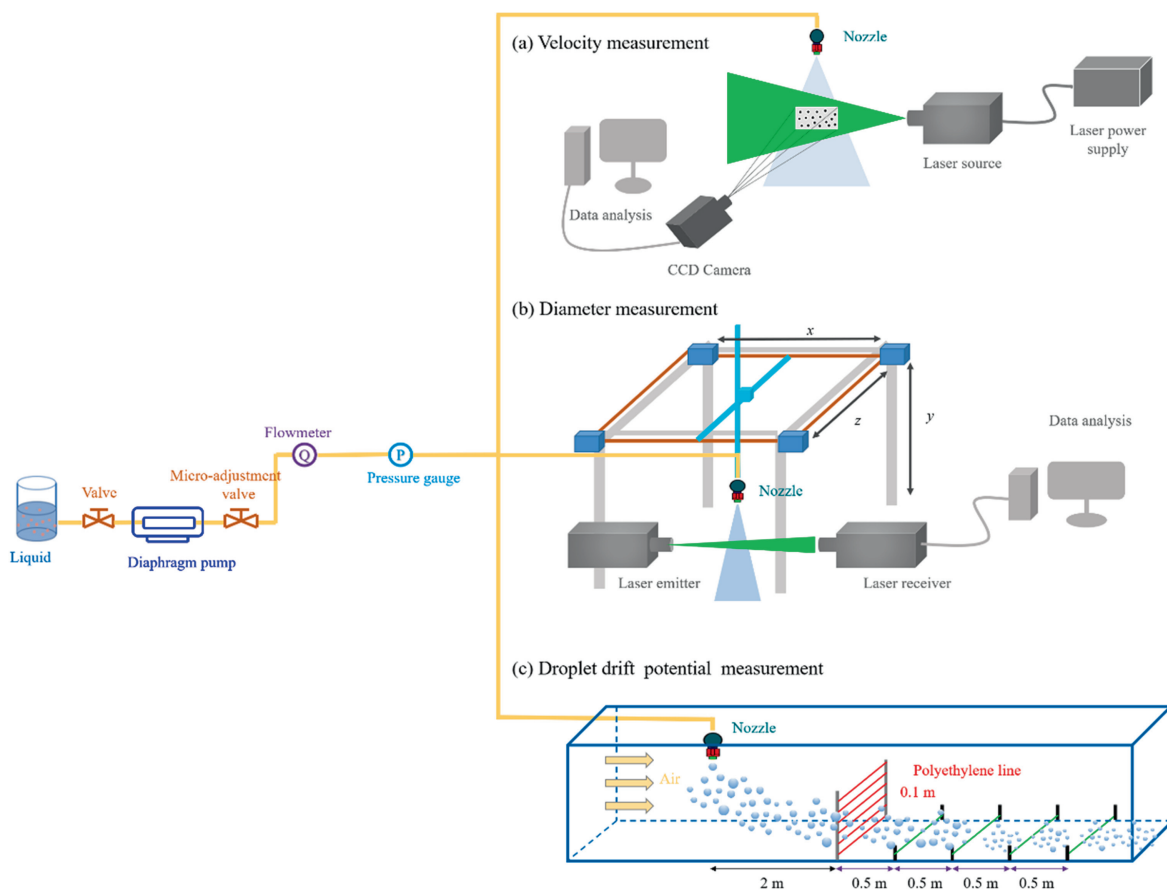


Fig. 1. The schematic of velocity measurement by PIV technology (a); the schematic of droplet diameter measurement (b); the schematic of drift potential assessment of spray droplets in the wind tunnel (c).

widely used in the PIV experiments, including the solid particle and liquid particle, which can improve the measurement accuracy. However, it's unnecessary to add the tracer particle when the atomized droplet with good scattering ability is taken as the measurement object. In this experiment, the water droplet has good imaging visualization performance and the droplet itself can act as the tracer particle.

The apparatus is mainly composed of the spray system, a laser lighting device (LWGL532-12 W-L, Beijing Laser wave Optoelectronics Technology Co., Ltd., China), a CCD camera device (FAS-TCAM Mini UX100, Photron, Japan), and a data analysis system. The water liquid was raised by the diaphragm pump and the flow rate was regulated by the micro-adjustment valve. The flow meter and pressure gauge were installed in front of the selected nozzle for monitoring the spray conditions. The laser with an emitting wavelength of 532 nm was used to illuminate the spray field. And the convex lens was arranged to produce a laser sheet with a beam waist thickness of 1 mm. The laser sheet plane was adjusted to coincide with the center plane of the spray field for the reduction of image defocus. The droplet itself acted as the tracer particle and was captured by the CCD camera when it was illuminated. The shooting direction of CCD camera was vertical to the plane of light sheet produced by the laser. The frame rate of CCD camera was set to 10,000 frame per second with a pixel resolution of 1280×480 . A 50 mm lens was used to obtain a field of view that was large enough to track the displacement of droplet, and the dimension of the actual region of interest (ROI) was calculated by the ruler. The height of CCD camera was adjusted vertically to capture the droplet movement in the different regions below the nozzle, as shown in Fig. 2. After recording, the illumination device was closed firstly. Then, the camera device and the diaphragm

pump were turned off. The recorded images were imported into the data analysis system to calculate the velocity distribution of spray droplets in the ROI. The interrogation window was set as 32×16 pixels to ensure that the droplet displacement between two successive images was less than one-quarter of the interrogation window length. The data accuracy was improved by the Gaussian sub-pixel fitting, and the vector correction was applied by the median filtering algorithm. The data processing was conducted through the Micro Vec V3 software developed by the company of "MicroVec, Inc., China". The velocity distribution in the ROI was averaged from 200 successive images and the average velocity contours were depicted in the Origin 2018 software.

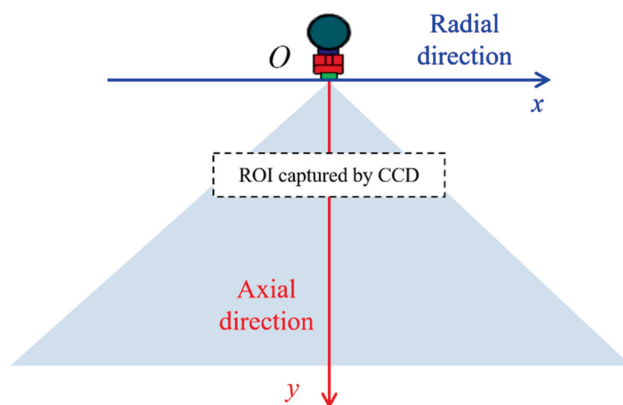


Fig. 2. The schematic of the measured spray area.

2.1.2. Diameter measurement and drift potential assessment

The schematic of the droplet measurement experiment is shown in Fig. 1(b). It mainly includes the spraying system, the three-dimensional displacement platform for nozzle movement, laser particle size analyzer (Winner318C, Jinan Winner Particle Instrument Stock Co., Ltd., China), and data collection and analysis system. Before spraying, the laser particle size analyzer was pre-heated to eliminate the effect of background. Adjusted the spraying pressure to 0.3 MPa, and then collected the data after the spraying pressure was stable. The diameter distribution at the measured point could be calculated according to the scattered light intensity when droplets were passing through the laser beam. The nozzle could move upwards or downward with an accurate distance by a controllable three-dimensional displacement platform to obtain the spatial diameter distribution along the axial direction.

The drift potential test experiment of spray droplets in the wind tunnel is illustrated in Fig. 1(c). It is composed of the wind generation apparatus with an array of axial-flow fans, the spraying system, the polyethylene line for collecting the drifting droplets, and the spectrophotometer for obtaining the droplet deposition amount onto the polyethylene lines. The sprayed liquid was fully mixed and dyed with 0.1% (mass) of Allura Red for the measurement of droplet deposition. Previous studies have shown the physiochemical properties of sprayed liquid cannot be changed after adding Allura Red, and the color almost doesn't fade [38]. The measured nozzle was installed at the height of 0.7 m from the ground of wind tunnel. The polyethylene lines were arrayed between 2.0 m and 4.0 m downwind from the nozzle with an interval of 0.5 m for assessing the drift potential of droplets in the horizontal direction. Similarly, the polyethylene lines were vertically arrayed between 0.1 m and 0.6 m from the tunnel ground with an interval of 0.1 m for assessment of vertical drift potential. During the spraying experiment, the air velocity was adjusted to $2.5 \text{ m}\cdot\text{s}^{-1}$ by changing the input power of fans to simulate the field environment. After the air velocity was stable, the spraying began and lasted for 10 s, and the power of fans was closed until all the droplets had deposited. The polyethylene lines were collected within the marked bags, and the distilled water of 40 ml was added. The Allura Red was washed ultrasonically, and then the amount of droplets deposited onto the polyethylene lines are quantitatively calculated by comparing the absorbance of the washed liquid and the standard solution of Allura Red, as shown in Eq. (1).

$$m = \frac{(A_s - A_b) \times F_{\text{cal}} \times V_w}{S_c} \times 1000 \quad (1)$$

where, m is the deposition amount of spray droplets onto the polyethylene line ($\text{mg}\cdot\text{cm}^{-2}$); A_s and A_b is the absorbance of the sample and the blank; F_{cal} is the calibration factor ($\text{mg}\cdot\text{L}^{-1}$); V_w is the volume of the washed liquid (ml); S_c is the collection area of a polyethylene line (cm^2).

To evaluate and compare the drift potentials of different nozzles, the horizontal distance-weighted average fallout deposition ($m_{h,\text{ave}}$) and the vertical height-weighted average fallout deposition ($m_{v,\text{ave}}$) were respectively calculated by Eqs. (2) and (3). It indicates that the drift loss will be more serious with the larger average fallout deposition.

$$m_{h,\text{ave}} = \frac{\int_{2.0}^{4.0} x \cdot m_h(x) dx}{\int_{2.0}^{4.0} x dx} \quad (2)$$

$$m_{v,\text{ave}} = \frac{\int_{0.1}^{0.6} y \cdot m_v(y) dy}{\int_{0.1}^{0.6} y dy} \quad (3)$$

where, $m_h(x)$, $m_v(y)$ is respectively the function of fallout deposition amount with the downwind distance from the nozzle and the height from the wind tunnel ground.

2.2. Movement model of spray droplet

The Eulerian–Lagrangian method was adopted to describe the droplet movement in the air due to the low volume fraction occupied by the discrete phase. The air velocity was assumed to be uniformly distributed along the vertical direction since the droplet behaviors within the limited height of 500 mm were focused in this paper and the air velocity fluctuation could be ignored. The droplet was assumed to be spherical as the deformation of the sub-micron pesticide droplet is very slight during spatial motion. The movement of pesticide droplet in the air was tracked by Newton's second law of motion. And the gravity, buoyancy and drag force were taken into consideration as depicted in Fig. 3, while other forces were assumed to be negligible. The detailed equations were expressed as follows.

$$\frac{d\mathbf{u}_p}{dt} = \mathbf{F}_d + \mathbf{F}_g + \mathbf{F}_b \quad (4)$$

$$\mathbf{F}_d = \frac{18\mu C_d Re}{24\rho_p d_p^2} (\mathbf{u}_a - \mathbf{u}_p) \quad (5)$$

$$Re = \frac{\rho_a d_p |\mathbf{u}_p - \mathbf{u}_a|}{\mu} \quad (6)$$

$$\mathbf{F}_g + \mathbf{F}_b = \frac{g(\rho_p - \rho_a)}{\rho_p} \quad (7)$$

where, $\mathbf{F}_d$, $\mathbf{F}_g$, $\mathbf{F}_b$ are the drag force, gravity, and buoyancy force exerted on the unit mass droplet ($\text{m}\cdot\text{s}^{-2}$); $\mathbf{u}_a$ is the air velocity ($\text{m}\cdot\text{s}^{-1}$); $\mathbf{u}_p$ is the droplet velocity ($\text{m}\cdot\text{s}^{-1}$); Δv is the relative velocity of droplet and air ($\text{m}\cdot\text{s}^{-1}$); ρ_a is the air density ($\text{kg}\cdot\text{m}^{-3}$); ρ_p is the droplet density ($\text{kg}\cdot\text{m}^{-3}$); d_p is the droplet diameter (m); C_d is the drag coefficient of droplet; μ is the molecular viscosity of air ($\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$); Re is the relative Reynolds number; g is the gravitational acceleration ($\text{m}\cdot\text{s}^{-2}$).

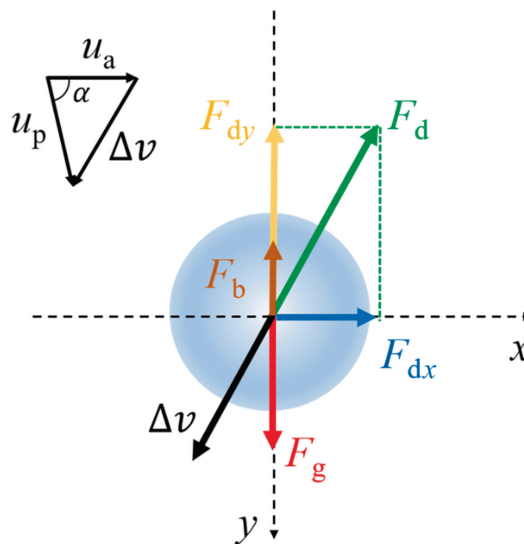


Fig. 3. The schematic of the forces exerted on the droplet.

The drag coefficient of droplet is largely related to Re and was calculated by the following equation.

$$C_d = \frac{a}{Re} + \frac{b}{Re^2} + c \quad (8)$$

where, a , b and c are empirical constants and depend on Re [39].

The differential equations that describe the droplet movement in the air were numerically solved by the finite difference method. The droplet position was updated at the interval of particle time step size until the droplet had deposited. After calculation, the evolutions of droplet velocity and dynamic force with the falling distance were depicted to compare the spatial behavior differences of pesticide droplets with different sizes.

3. Results and Discussion

3.1. Spatial distribution and rapid reduction of droplet velocity

Fig. 4(a) shows the droplet velocity distribution of the nozzle IDK120 015 under the pressure of 0.4 MPa. It can be clearly seen from the contour color that the larger droplet velocities are mainly distributed within the region of 100 mm below the nozzle, and the largest velocity is about $10 \text{ m}\cdot\text{s}^{-1}$. Besides, the droplet velocity is reducing rapidly as the droplet is falling. In order to quantitatively describe the ratio of velocity reduction, the evolutions of droplet velocity along the radial and axial directions were further depicted. Fig. 5 displays the droplet velocity evolution at the axial centerline ($x = 0 \text{ mm}$) of spray field with the falling distance. It shows that the droplets nearly decelerate linearly with the falling distance. When the droplet is falling a distance of 180 mm, the velocity reduces to $2 \text{ m}\cdot\text{s}^{-1}$ from the initial $10 \text{ m}\cdot\text{s}^{-1}$, and the attenuation ratio is about 80%. The droplet velocity distribution along the radial direction is plotted in Fig. 6(a). It can be found that the velocity distribution shows good symmetry near the nozzle (such as $y = 40 \text{ mm}$) with the maximum velocity in the center zone and the minimum velocity at the edge of the spray field. As the droplets continue to fall, both the droplets in the center zone and edge zone of ROI are gradually decelerating. Meanwhile, the velocity differences between the two regions are narrowing, finally resulting in a slight fluctuation of droplet velocity along the radial direction, such as the veloc-

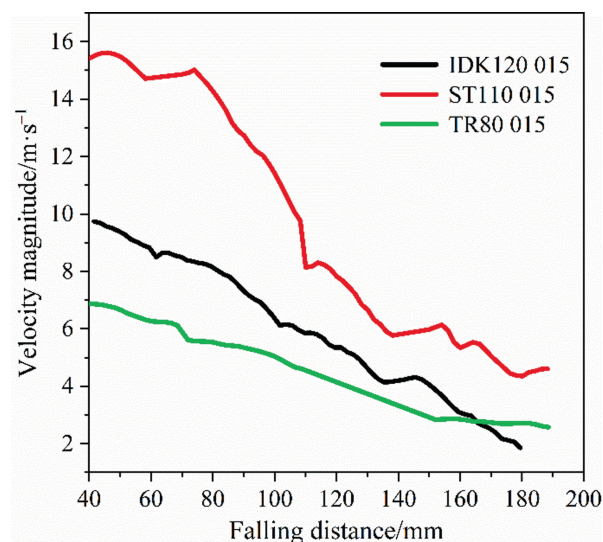


Fig. 5. The evolution of droplet velocity at the centerline ($x = 0 \text{ mm}$) with falling distance for three nozzles under the pressure of 0.4 MPa.

ity is fluctuating around $3 \text{ m}\cdot\text{s}^{-1}$ at $y = 160 \text{ mm}$. In a word, the results suggest that all the droplets within the spray field of IDK120 015 are rapidly decelerating, and the velocity attenuation at the center zone is more obvious than that at the edge zone. Finally, the droplet velocity tends to fluctuate slightly and stably along the radial direction.

Fig. 5. The evolution of droplet velocity at The droplet velocity distribution for the nozzle ST110 015 is shown in Fig. 4(b), and the droplet velocity distributions along the axial centerline ($x = 0 \text{ mm}$) and radial directions are also extracted in the same way as the nozzle IDK120 015. Similar to IDK120 015, the contour color shows that the droplet is also decelerating rapidly, and the larger droplet velocities are distributed within the region of 100 mm below the nozzle with the maximum velocity of about $16 \text{ m}\cdot\text{s}^{-1}$. Fig. 5 shows that the velocity reduces to $5 \text{ m}\cdot\text{s}^{-1}$ from the initial $16 \text{ m}\cdot\text{s}^{-1}$ with an attenuation ratio of about 68% when

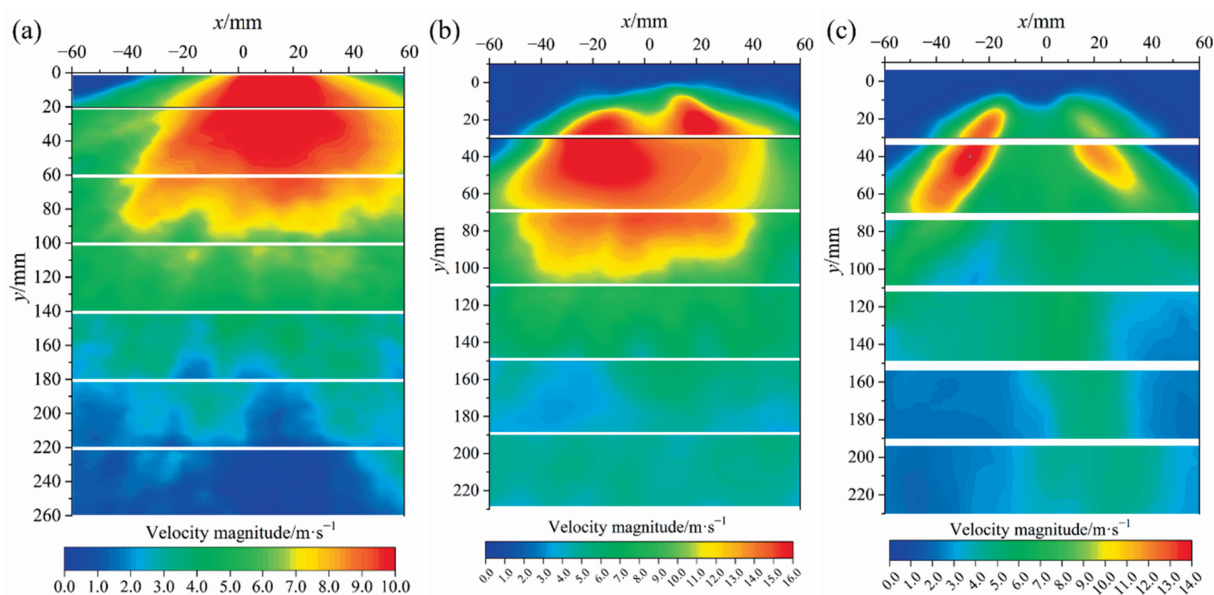


Fig. 4. The droplet velocity distribution contour for the nozzle IDK120 015 (a), ST110 015 (b) and TR80 015 (c) under the pressure of 0.4 MPa. The centerline ($x = 0 \text{ mm}$) with falling distance for three nozzles under the pressure of 0.4 MPa.

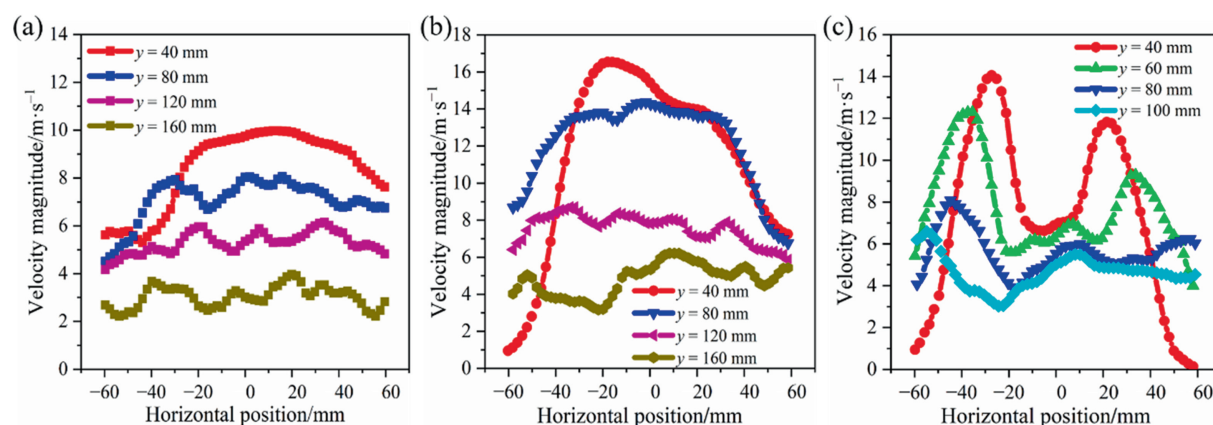


Fig. 6. The droplet velocity distribution along the radial direction at the different falling planes for the nozzle IDK120 015 (a), ST110 015 (b) and TR80 015 (c) under the pressure of 0.4 MPa.

the droplet is dropping by 200 mm. The contour results of velocity distribution within the region of 30 mm below the nozzle seem to be singular in Fig. 4(b). It is attributed to the existence of the liquid sheet and the massive new-formed droplets during the primary atomization near the nozzle, leading to an extremely strong light-reflected intensity. And the droplets in the highly lighted regions are unable to be correctly identified by the post-processing algorithm. The spatial evolution of droplet velocity along the radial direction for ST110 015 in Fig. 6(b) is similar to that of IDK120 015 in Fig. 6(a) due to the same fan-shaped spray pattern. The velocity presents the final trend of weak radial fluctuation far away from the nozzle transitioning from the single peak distribution near the nozzle. Compared with IDK120 015, however, the droplets of ST110 015 have a higher initial velocity (Fig. 5), which is mainly originated from the Venturi effect caused by the air induction for IDK120 015 [18,30].

Fig. 4(c) shows the results of droplet velocity distribution for TR80 015 under the pressure of 0.4 MPa. It can be seen that the droplet velocity presents a double peak distribution near the nozzle with the maximum velocity located at the edge of spray profile and the minimum velocity distributed inside the spray field. This is because the TR80 015 is a hollow cone nozzle, and droplets are generated by the rim breakup of thin liquid sheet at the edge [40]. The droplets inside the spray field mainly come from the inward entrainment process induced by the uneven pressure distribution due to the velocity difference between inside and outside [41]. When the droplets are dropping, the velocity at the edge decreases rapidly to $7 \text{ m}\cdot\text{s}^{-1}$ at $y = 100 \text{ mm}$ from the initial $14 \text{ m}\cdot\text{s}^{-1}$ at $y = 40 \text{ mm}$, while the velocity inside the spray field changes insignificantly (Fig. 6(c)). It's because that the diameter of the entrained droplet is small, and the droplet velocity gradually reaches the terminal settling velocity, subsequently falling with a nearly constant velocity as shown in Fig. 5.

In summary, the indoor PIV experiments show that the spatial droplet velocity all reduces rapidly with the falling distance for three distinctive nozzles, even though there are obvious differences in the breakup pattern of liquid sheet and the formation mode of droplets. Also, the velocity differences along the radial direction are gradually narrowing.

3.2. Spatial velocity evolution of droplets with different diameters in crossflow

During the pesticide spraying in the field, the rapid reduction of droplet velocity is not only related to the traveling motive force and the spatial drift loss, but also determines the initial velocity

magnitude and direction of the droplet entering the target canopy. Therefore, the velocity evolutions of droplets with different sizes were numerically calculated in crossflow to simulate the outdoor pesticide spraying.

The PIV experiment results of droplet velocity were used to verify the accuracy of numerical models. The comparisons between the experimental results and numerical results are displayed in Fig. 7. It shows that the mean relative error between them is less than 10%, suggesting that the numerical models can effectively predict the spatial velocity evolution of droplets moving towards the target.

The size of pesticide droplets generated by the agricultural nozzles ranges from tens to hundreds of microns, and the spray height for the boom sprayer is about 500 mm in the field [16,42]. Based on this, the velocity magnitude and direction evolutions for droplets between $50 \mu\text{m}$ and $300 \mu\text{m}$ were numerically predicted within the falling distance of 500 mm under the natural crosswind of $2 \text{ m}\cdot\text{s}^{-1}$, as shown in Fig. 8. It can be found that the velocities of droplets with different sizes all attenuate rapidly after they are leaving the nozzle, and the attenuation rate is significantly related to the droplet diameter. In contrast, the velocities of droplets smaller than $150 \mu\text{m}$ are reducing sharply to the air velocity, and the abilities to maintain the initial direction are also weakening. For example, the velocity magnitude of the droplet with $100 \mu\text{m}$ reduces considerably from the initial value of $15 \text{ m}\cdot\text{s}^{-1}$ to the crosswind of $2 \text{ m}\cdot\text{s}^{-1}$ when it only drops by 185 mm. Meanwhile,

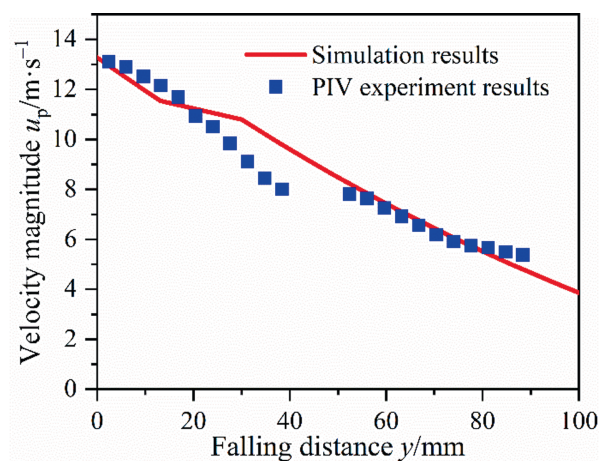


Fig. 7. Comparisons between the simulation results and the PIV experiment results.

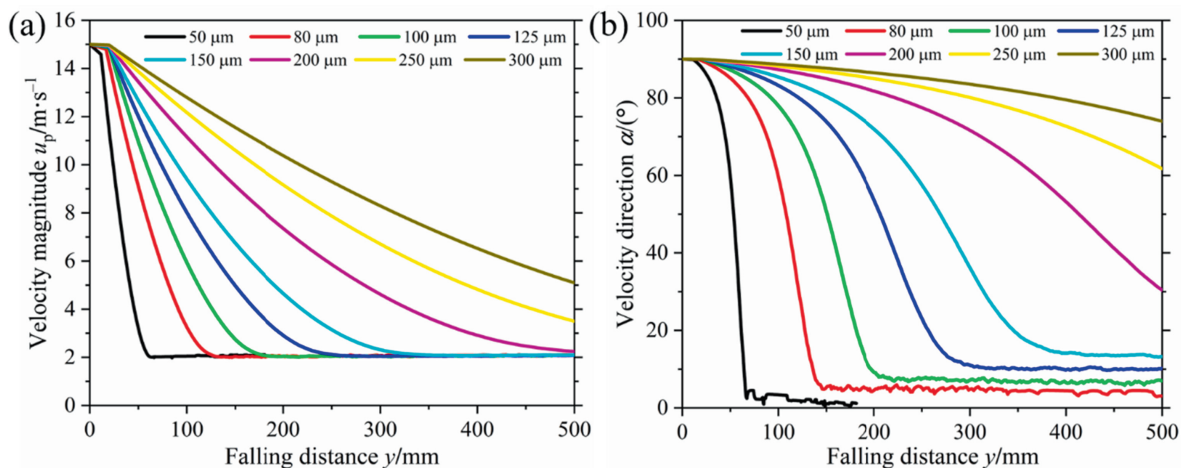


Fig. 8. The velocity magnitude (a) and direction (b) evolution of droplets with different sizes under the crosswind velocity of $2 \text{ m}\cdot\text{s}^{-1}$, α is the relative direction of the droplet and the air as illustrated in Fig. 3.

the relative velocity direction between the droplet and the air is about 6° , which is nearly consistent with the crosswind direction. The continuous slight fluctuation in the velocity direction indicates that the droplet is constantly shaking up and down. However, the velocity reduction rates of droplets larger than $150 \mu\text{m}$ are obviously slowing and they still have good abilities to maintain the initial movement direction when dropping by 500 mm . For instance, the droplet with $250 \mu\text{m}$ is going to enter the canopy with the final velocity of $3.5 \text{ m}\cdot\text{s}^{-1}$ and the angle of 61° when dropping by 500 mm .

It suggests that the final evolution results of the spatial velocity magnitude and direction are determined together by the air conditions and the droplet diameter. Fig. 9 summarizes the final spatial velocity results, or the initial conditions of entering the target canopy, of droplets between $50 \mu\text{m}$ and $300 \mu\text{m}$ under the air velocity from $1 \text{ m}\cdot\text{s}^{-1}$ to $3 \text{ m}\cdot\text{s}^{-1}$ when droplets are dropping by 500 mm . It can be found that the final spatial velocities of droplets smaller than $150 \mu\text{m}$ are almost equal to the air velocity, but not related to the droplet diameter itself. Meanwhile, the relative angle between the droplet and the air entering the canopy is less than 20° . For droplets larger than $150 \mu\text{m}$, however, the final spatial velocities gradually increase with the droplet diameter, but are slightly affected by the air velocities. The droplets tend to obliquely enter the canopy with a relatively larger angle.

It can be inferred that the droplet with $150 \mu\text{m}$ is nearly the sensitive boundary of the droplet whose spatial velocity evolution is affected by the air conditions. This means that it is difficult for the smaller droplets, such as the droplets below $100 \mu\text{m}$, to deposit on the target surface. They are more prone to float in the atmosphere and drift further under the action of the crosswind. For the larger droplets, the droplet's ability to maintain the initial velocity direction can be improved, and they can penetrate the target canopy at a certain angle, leading to an oblique impact of droplet on the leaf surfaces. Therefore, much more attention should be focused on these sensitive droplets for the improvement of pesticide utilization efficiency in the field application. On the one hand, the initial proportion of these easily drifting droplets is supposed to be reduced as much as possible during the atomization process by the combined optimization of the liquid properties and the operating conditions. Besides, the spatial behaviors of these sensitive droplets are encouraged to be regulated by facilitating the collision probability with other droplets.

3.3. Mechanism on the rapid reduction of droplet velocity dominated by diameter

Both the indoor PIV experiments and the outdoor numerical results under crosswind show that the droplet velocity reduced rapidly after leaving the nozzle, especially for the droplets below $150 \mu\text{m}$. To figure out the mechanism of the velocity evolution dominated by diameter, in this section, the dynamic forces exerted on the droplet were tracked during spatial motion. The forces were respectively decomposed along the horizontal and vertical directions to investigate the detailed drift behaviors of pesticide droplets, as presented in Fig. 3.

Fig. 10(a) and (b) illustrate the dynamic evolution of the vertical and horizontal drag force exerted on the droplets with $100 \mu\text{m}$ and $200 \mu\text{m}$. The initial vertical drag force exerted on the droplet with $100 \mu\text{m}$ is nearly 230 times the difference between gravity and buoyancy, also named “the net gravity”. It results in the rapid reduction of vertical velocity due to the hindrance of drag force (Blue dotted line in Fig. 10(a)). During motion, the vertical drag force gradually decreases (Blue solid line in Fig. 10(a)), for the relative velocity between droplet and air along the vertical direction is slowly narrowing. The vertical velocity of the droplet nearly decelerates closely to $0 \text{ m}\cdot\text{s}^{-1}$ at the position of 200 mm below the nozzle when the vertical drag force equals the net gravity.

The droplet starts to accelerate along the horizontal direction since the initial horizontal drag force acts as a driving force (Red dotted line in Fig. 10(a)). Similar to the evolution of vertical drag force, the horizontal drag force also reduces during motion due to the reduction of the relative horizontal velocity between droplet and air (Red solid line in Fig. 10(a)). When the horizontal velocity of droplet increases to the crosswind velocity of $2 \text{ m}\cdot\text{s}^{-1}$, both the relative velocity and the horizontal acceleration almost equal to 0. Then, the droplet will move at a uniform velocity along the horizontal direction and drift further downwind.

Regarding the bigger droplet with $200 \mu\text{m}$, the dynamic evolution of horizontal and vertical drag force is similar to that with $100 \mu\text{m}$. However, the most obvious difference between the droplets is the reduction rate of the velocity and drag force. The droplet with $200 \mu\text{m}$ can impact the target surface with a vertical velocity of about $1.0 \text{ m}\cdot\text{s}^{-1}$ when dropping by 500 mm , while the vertical velocity of droplet with $100 \mu\text{m}$ has nearly reduced to 0 when just dropping by 200 mm . This is mainly due to the differ-

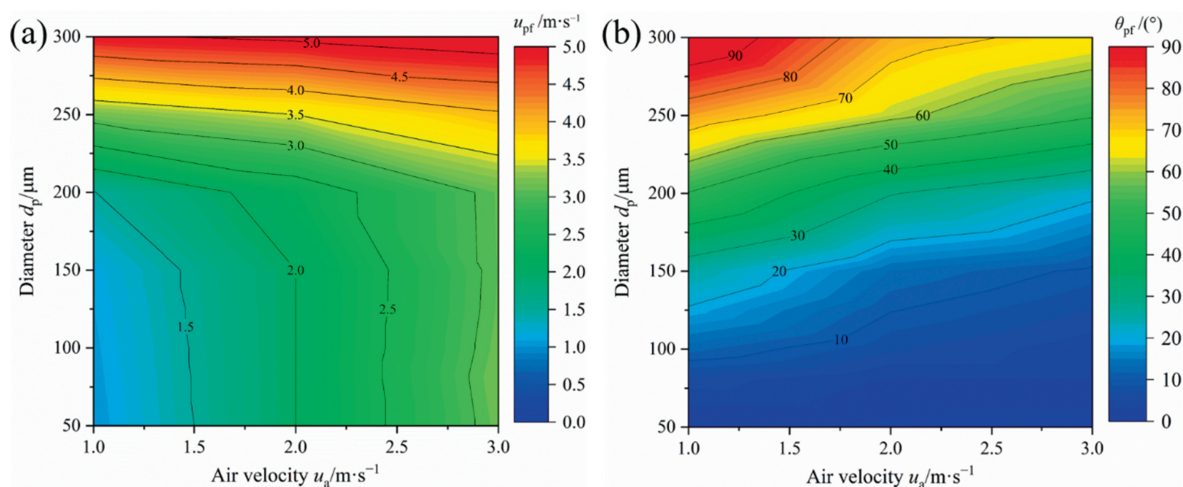


Fig. 9. The velocity magnitude (u_{pr}) and direction (θ_{pr}) of droplets with different diameters when droplets are falling 500 mm under various velocities.

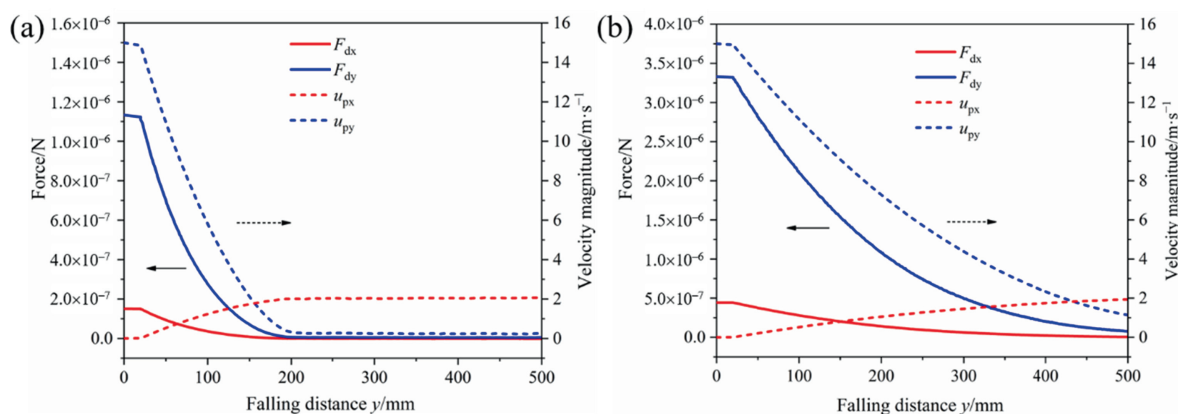


Fig. 10. The evolution of the forces exerted on the droplet with 100 μm (a) and 200 μm (b). (The solid lines refer to the force evolutions at the left axial and the dashed lines refer to the velocity evolutions at the right axial.)

ence in the ratio of the vertical drag force to the net gravity at the initial position. The ratio for droplet with 200 μm is about 84, nearly one-third that of the droplet with 100 μm . It suggests that the larger droplet has a stronger ability to maintain the initial kinetic energy and moving direction. However, the resistance exerted on the smaller droplet is considerably larger than its net gravity, and thus it's difficult to deposit on the target surface.

The results show that the initial ratio of vertical drag force to net gravity determines the evolution of droplet velocity in the subsequent spatial motion. This ratio represents the competition of the drag force and the motive force of droplet moving to the target, which is mainly determined by the droplet diameter and the relative direction between the droplet and the air. Fig. 11 shows the combined effects of the droplet diameter and the relative direction on the ratio. It can be seen that as the droplet size decreases, the order magnitude of the ratio increases exponentially from tens to hundreds under all relative directions. The ratio is nearly less than 100 for the droplets bigger than 150 μm , and it sharply increases as the droplet size gradually decreases from 150 μm . Compared with the droplet diameter, the relative direction causes a weaker effect on the ratio, illustrating that the droplet size is mainly responsible for the competition of the traveling resistance and motive force, as well as the spatial evolution of the droplet velocity.

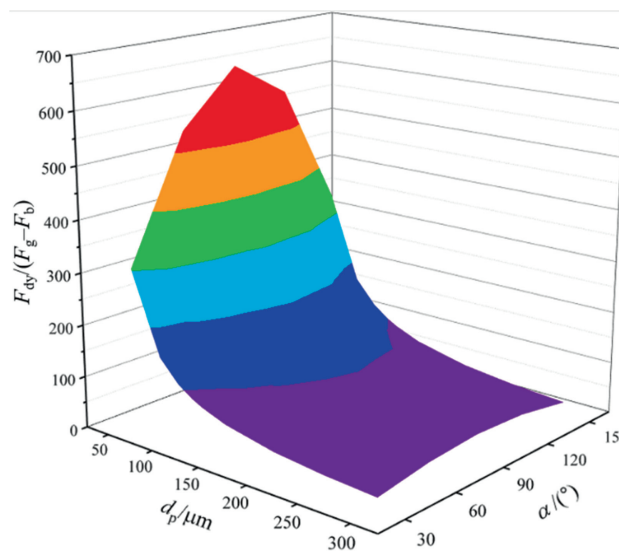


Fig. 11. The ratio of the vertical drag force and the net gravity initially exerted on the droplets with different sizes under various relative directions.

3.4. Spatial diameter distribution and drift potential assessment of spray droplets in the wind tunnel

Fig. 12(a) presents the volume median diameter of droplets, D_{v50} , at the different axial heights for three nozzles, showing that the droplet diameter decreases firstly and then nearly keeps constant with the falling distance. It's mainly because that the liquid sheet breakup and the droplet formation happen within the region of 50 mm, where there are a few liquid ligaments or massive droplets, leading to the higher diameter near the nozzle. And as the droplets continue to disperse, the diameter is going to reduce. In contrast, the IDK 120 015 produces the largest droplets, which are caused by the bubble contained in the droplet due to the inhalation of air during the atomization process. The diameter difference between the TR80 015 and the ST110 015 only occurs near the nozzle, which is attributed to the pattern of sheet breakup. The droplets of ST110 015 are produced by the wave breakup of liquid sheet, leading to a longer breakup length than TR80 015 [17]. After the primary atomization is completed, the diameter difference between these two nozzles is slight.

Fig. 12(b) shows the proportion of easily drifting droplets at the corresponding measured positions. At $y = 50$ mm, TR80 015 has the

largest proportion of droplets smaller than $80\ \mu\text{m}$. It is because that TR80 015 is a hollow cone nozzle, and the smaller droplets are going to be entrained into the inside of cone due to the pressure difference near the nozzle, leading to smaller droplets in the center of spray field. And ST110 015 is a flat-fan nozzle, the entrainment of smaller droplets is not strong near the nozzle than TR80 015. After the atomization is completed, the entrainment effect of ST110 015 is stronger due to the higher droplet velocity than TR80 015. Therefore, the proportion of droplets smaller than $80\ \mu\text{m}$ for ST110 015 gradually increases below 100 mm from the nozzle. Regardless of the measured position, IDK120 015 has the largest droplet and the minimum proportion of easily drifting droplets.

It indicates that the difference of diameter distribution near the nozzle is mainly caused by the atomization pattern of the nozzle itself, and the droplet velocity gradually causes significant impacts on the diameter as the droplet continues to fall.

The drift potential results of three nozzles under the air velocity of $2.5\ \text{m}\cdot\text{s}^{-1}$ in the wind tunnel experiments are presented in Fig. 13(a) and (b). It can be seen that the horizontal fallout deposition gradually reduces with the downwind distance from the nozzle. The IDK 120 015 has the weakest drift potential due to the

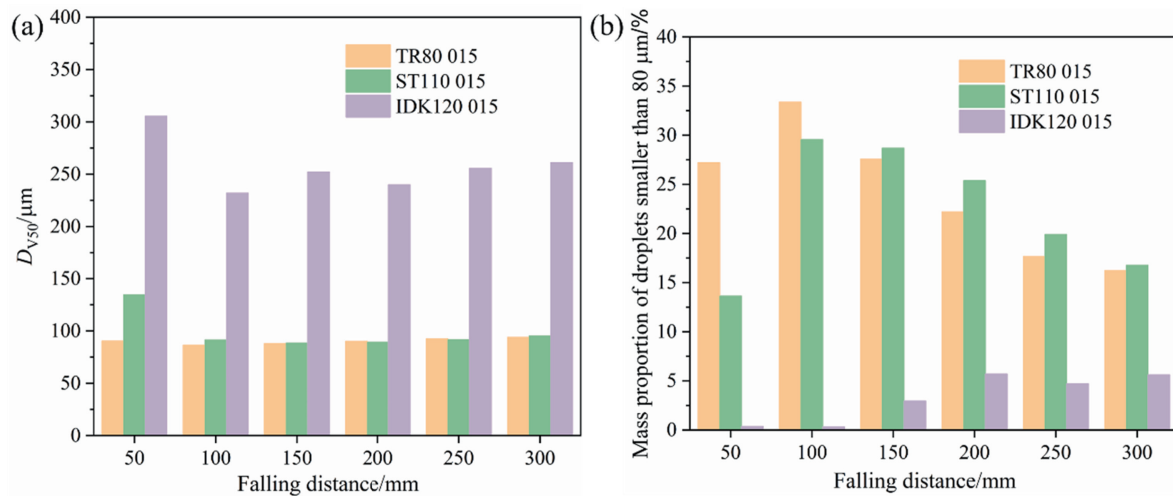


Fig. 12. The volume median diameter of droplets, D_{v50} (a), and the mass proportion of droplets smaller than $80\ \mu\text{m}$ at the different axial positions below the three nozzles (b).

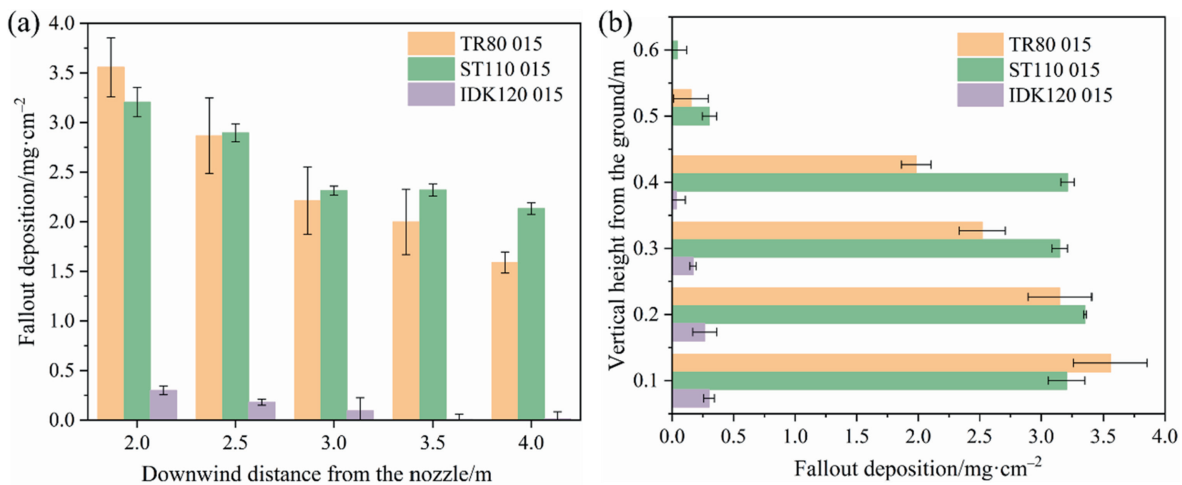


Fig. 13. The horizontal (a) and the vertical (b) fallout deposition of droplets in the wind tunnel experiments.

Table 2

The horizontal distance-weighted and the vertical height-weighted average fallout deposition of three nozzles

Nozzle type	$m_{h,ave}/\text{mg}\cdot\text{cm}^{-2}$	$m_{v,ave}/\text{mg}\cdot\text{cm}^{-2}$
TR80 015	2.30	1.91
ST110 015	2.51	2.01
IDK120 015	0.08	0.16

Table 3

The horizontal distance-weighted and the vertical height-weighted average fallout deposition of three nozzles after adding Beidatong

Nozzle type	$m_{h,ave}/\text{mg}\cdot\text{cm}^{-2}$	$m_{v,ave}/\text{mg}\cdot\text{cm}^{-2}$
TR80 015	1.11	0.68
ST110 015	1.57	1.39
IDK120 015	0.06	0.12

largest droplet diameter and the minimum proportion of easily drifting droplets. While the droplet diameter difference is negligible between the ST110 015 and TR80 015, the proportion of smaller droplets for ST110 015 is more than TR80 015. Therefore, ST110 015 has the strongest drift potential among three distinctive nozzles. Similarly, the vertical fallout deposition of IDK120 015 is the least, regardless of the vertical height from the ground. The vertical fallout deposition of TR80 015 is decreasing with the vertical height, however, that of ST110 015 is much more within the height from 0.1 m to 0.4 m. It also means that ST110 015 has the strongest drift potential. To quantitatively compare the drift potentials of three nozzles, the horizontal distance-weighted average fallout deposition ($m_{h,ave}$) and the vertical height-weighted average fallout deposition ($m_{v,ave}$) are shown in Table 2. It suggests that ST110 015 has the most serious drift loss, followed by TR80 015 and IDK120 015 in both horizontal and vertical direction. Compared with ST110 015, the horizontal drift potential of TR80 015 and IDK120 015 decreases by 8.37% and 96.81% respectively. And the vertical drift potential reduces by 4.98% and 92.04% respectively (see Table 3).

The droplet diameter considerably determines the spatial velocity evolution of droplet itself, and in turn, the droplet velocity will cause impacts on the spatial diameter distribution. Finally, the droplet drift loss is determined together by the combined effects of the droplet diameter and velocity, especially the proportion of easily

drifted droplets. Therefore, improvement of droplet diameter distribution is a prospecting measure to regulate the droplet drift behavior and reduce the spatial drift loss. From it, 1.0% (volume) of Beidatong (Hebei Ming Shun Agricultural Science and Technology Co., Ltd., China), a functional adjuvant of plant oil, was added into the water liquid to change the physicochemical properties for regulating the droplet diameter distribution. The addition of Beidatong reduces the liquid surface tension to $0.0295 \text{ N}\cdot\text{m}^{-1}$ and increases the viscosity to $1.70 \text{ mPa}\cdot\text{s}$. The improvement effects of droplet diameter for three nozzles are presented in Fig. 14, showing the increment of droplet diameter and the considerable proportion reduction of easily drifted droplets due to the addition of Beidatong. It indicates that the initial distribution uniformity of droplet diameter can be improved by the additives that increase the viscosity of liquid and thus inhibit the generation of smaller droplets. The effects of adding Beidatong on the droplet drift of three nozzles in the wind tunnel are presented in Fig. 15. It can be seen that compared with the pure water liquid, both the horizontal and vertical fallout deposition reduces significantly after adding Beidatong, especially for the TR80 015 and the ST110 015 nozzle. Similarly, the distance-weighted and height-weighted average fallout deposition are calculated for quantitatively evaluating the effect of Beidatong on the drift reduction. In the downwind direction, the drift reduction ratios are 51.74%, 37.45% and 25.00%, respectively for the TR80 015, ST110 015 and IDK120 015. It suggests that the addition of Beidatong has better effects of reducing the drift loss for TR80 015 and ST110 015 than IDK120 015, for the lowest drift deposition of IDK120 015 without Beidatong.

During pesticide spraying, the biological effect of pesticide is the comprehensive results of liquid atomization, spatial drift, interfacial deposition, and translocation inside the target. Bigger droplets have the stronger anti-drift ability but are prone to runoff from the target surface. Although smaller droplets tend to drift further in crossflow, they are easily absorbed and translocated inside the target. It's of great significance for improving the pesticide utilization efficiency to select the suitable nozzle in terms of the growing period and the application site. The IDK120 015 nozzle with bigger diameter is more suitable for herbicide spraying in bare land or low-growing crop with high spray volume. And it's advisable to select the ST110 015 or TR80 015 nozzle with smaller diameter to spray insecticides and fungicides in the higher target crop, and they are also suitable to be equipped onto the aerial spray vehicle with the low or ultralow spray volume for improving

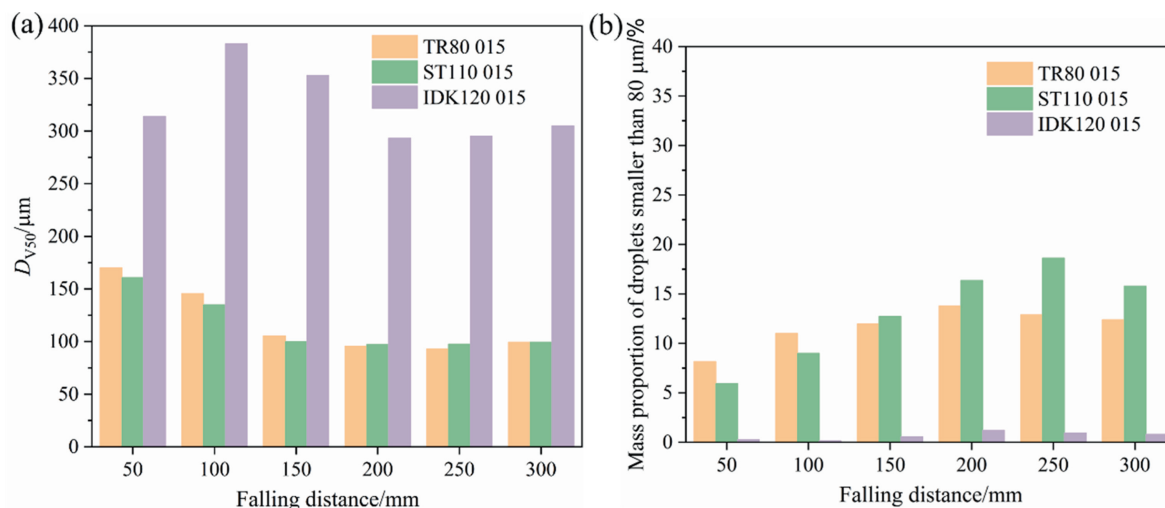


Fig. 14. The volume median diameter of droplets, D_{v50} (a), and the mass proportion of droplets smaller than $80 \mu\text{m}$ at the different axial positions below the three nozzles (b) after adding Beidatong.

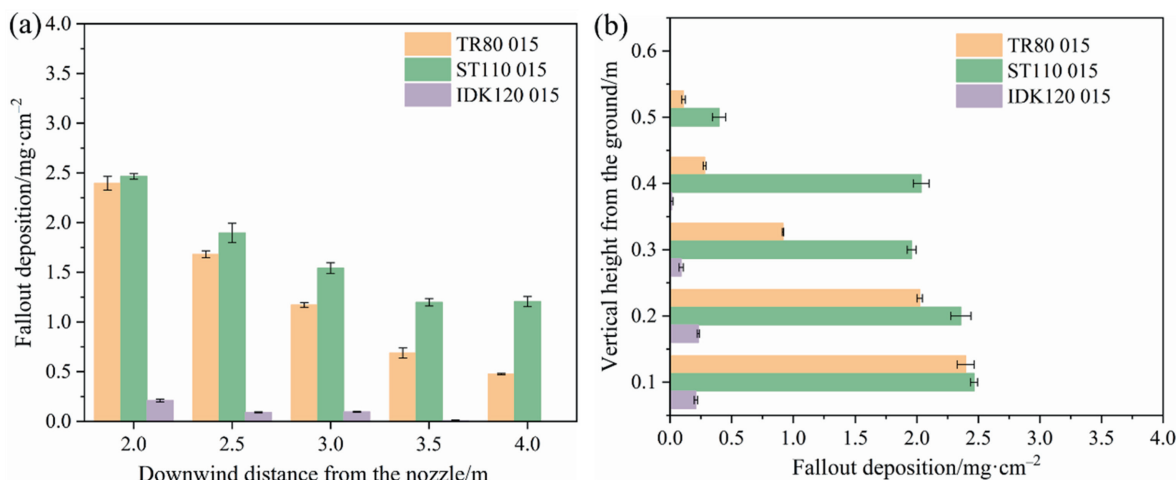


Fig. 15. The horizontal (a) and the vertical (b) fallout deposition of droplets after adding Beidatong in the wind tunnel experiments.

the coverage on the target surface. Meanwhile, adding the functional adjuvant, such as mineral oil, vegetable oil, and in homogeneities, can change the interaction force between the molecules inside the origin pesticide liquid and the interfacial membrane structure, resulting in the modification of the liquid physicochemical properties, such as surface tension and viscosity. Then, the thickness of the liquid sheet and its breakup position can be changed in the primary atomization process, thus affecting the diameter distribution of droplets. The proportion reduction of easily drifted droplets will greatly improve the uniformity of spray droplets, finally weakening the spatial drift loss and increasing the utilization efficiency of pesticide in the field spraying.

4. Conclusions

The spatial evolution of droplet velocity can determine both the drift loss and the deposition behavior onto the target surface. In this paper, the velocity distributions of spray droplets after leaving the nozzle were measured by PIV technology, and the mechanism of velocity reduction difference dominated by the droplet diameter in crossflow was clarified by dynamic force analysis. Also, the drift potentials of spray droplets before and after regulation of diameter distribution were evaluated by the wind tunnel experiments. The major conclusions are as follows.

- (1) The spatial velocity of spray droplets all reduces rapidly with the falling distance within the region of 200 mm below the nozzle, and the reduction ratio is between 50%–80%. Besides, the velocity difference along the radial direction is gradually weakening, and finally the velocity tends to fluctuate slightly.
- (2) Under the crosswind, the droplets below 150 μm decelerate rapidly to the air velocity and prefer to enter the canopy or drift further nearly with the air direction. The droplets above 150 μm tend to obliquely enter the canopy with a larger initial velocity and angle.
- (3) The difference in velocity reduction is dominated by the competition of vertical drag force and net gravity. As the droplet diameter decreases, the traveling resistance will exponentially increase, leading to the longer residence time.
- (4) In the wind tunnel experiments, the nozzle ST110 015 has the most drift loss, followed by TR80 015 and IDK120 015. The addition of Beidatong can reduce the drift loss by

51.74%, 37.45% and 25.00%, respectively for the TR80 015, ST110 015 and IDK120 015 mainly due to the mass proportion reduction of easily drifting droplets.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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