DEPOSITION PERFORMANCE OF HYDRODYNAMIC ULTRASONIC ATOMISING NOZZLES WITH DIFFERENT SPRAY PARAMETERS
/
不同喷雾参数对流体动力式超声雾化喷嘴的沉积性能研究

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ABSTRACT
In order to study the spraying effect of hydrodynamic ultrasonic atomizing nozzle under different spraying methods, and to investigate the practical application effect of hydrodynamic ultrasonic atomizing nozzle in agriculture, the atomization angle test and droplet size test under different spraying conditions were designed. Different spraying conditions atomization angle test and droplet size test were designed, the test results data were recorded, the pattern of change of the data was observed, and the data were fit to give the data changes in line with the functional equation; different spraying conditions and different corn leaf position droplet deposition coverage test were designed and the value of the deposition coverage of each position was recorded. The results showed that: the maximum value of the variation of atomization angle under different spraying conditions was 75.49°, and the minimum value was 14.49°; the maximum value of the variation of droplet size was 18.23 μm, and the minimum value was 4.78 μm; and the droplet deposition coverage was the highest in the mid-leaf position of the upper and lower leaves of the maize when the input air pressure was 0.3 MPa, which was 86.98% and 46.97%, respectively. Fitting the atomization angle data and droplet size data, the R^2 of the binomial fit was 0.85 and 0.94, respectively, and the Adjusted R^2 was 0.87 and 0.88, respectively, which made the fitting function meaningful and the fitting accuracy high. The hydrodynamic ultrasonic atomizing nozzle has a great advantage in generating small droplet sizes and performs well in deposition effect, and the experimental results can provide a reference for the research of hydrodynamic nozzles in the application technology.

摘要
为研究流体动力式超声雾化喷嘴在不同喷雾方式下喷雾效果，探究流体动力式超声雾化喷嘴在农业中实际应用效果。设计不同喷雾条件下雾化角试验和雾滴粒径试验，对试验结果数据进行记录，观测数据变化规律，并对数据进行拟合，给出符合数据变化的函数关系式；设计不同喷雾条件及不同玉米叶位置雾滴沉积覆盖率试验并对各位置的沉积覆盖率值进行记录。试验结果表明：不同喷雾条件下雾化角变化最大值为 75.49°，最小值为 14.49°；雾滴粒径变化最大值为 18.23μm，最小值为 4.78μm；在输入气压为 0.3MPa 时，玉米上、下叶的叶中位置雾滴沉积覆盖率最高，分别为 86.98%和 46.97%。对雾化角数据和雾滴粒径数据进行拟合，二项式拟合的 R^2 分别为 0.85 和 0.94，Adjusted R^2 分别为 0.87 和 0.88，拟合函数有意义且拟合精度较高。流体动力式超声雾化喷嘴在产生小雾滴粒径有着很大优势并在沉积效果上表现优异，试验结果可为流体动力式喷嘴在施药技术方面的研究提供参考。

INTRODUCTION
During plant protection application, *Hewitta J et al., (2008),* pointed out that ideally all the droplets of the liquid should be effectively deposited in the target area. However, *Allan S. Felsot et al., (2010),* state that it is not possible to avoid spray drift completely but it can be minimized by using best-management practices. *Hiltz et al., (2013),* showed that in the actual operation process due to the main factors such as spraying parameters (e.g., spraying pressure, atomisation angle, droplet size) and environmental and meteorological conditions (e.g., wind speed) will affect the droplet drift.

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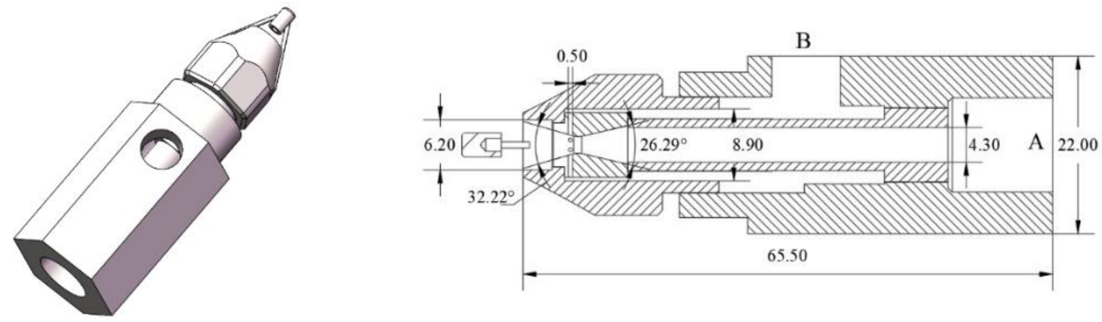
Huang Y.B. et al., (2013), pointed out that the droplet drift will cause the phenomena of soil environment pollution, part of the pesticide loss and pesticide utilisation rate reduction. *Maghsoudi H. et al., (2015),* pointed out that ultra-low volume spraying can improve the utilisation rate of pesticides, reduce the cost of pesticide use and pollution to the environment, and is a kind of application technology that is strongly promoted in the field of plant protection operations. *Wen S. et al., (2016), Yan X.J. et al., (2021),* found that compared to the conventional way of applying pesticides, 30% of pesticides can be saved. At this stage, the main way to achieve this technology is mostly pressure atomisation, centrifugal atomisation and electrostatic atomisation, or a combination of one or more atomisation methods, *Zhang J.T. et al., (2016),* showed that the above methods are complicated in structure and high in cost. Ultrasonic atomisation method generates small and uniform droplets and its application in agriculture has been explored by *Gao J.M. et al., (2017)*. *Lu D.P. et al., (2017),* pointed out that ultrasonic atomisation technology is mechanically divided into piezoelectric and hydrodynamic, and the former has a complex structure, high cost and energy consumption and low atomisation capacity, which is difficult to meet the actual needs of agriculture despite the innovation and improvement made by *Wu C.Q. et al. (2021)*. *Wu G.G. et al., (2021),* pointed out that the latter has excellent atomisation performance, *Park J. et al., (2022),* showed that wind field can affect the deposition coverage of droplets, *Tian Z. et al., (2022),* showed that the presence of a wind field can increase the penetration of droplets between the blades, *Liu C. et al., (2023),* showed that a conical wind field can increase the deposition coverage of droplets, and *Butler M.C. et al., (2017),* showed that downwind field reduces the drift of droplets. Therefore, *He R. et al., (2019) and Jiang C. et al., (2019),* pointed out that the hydrodynamic ultrasonic atomisation technology has great potential to achieve ultra-low-volume spraying in facility agriculture and ground plant protection operations. In order to investigate the application effect of hydrodynamic ultrasonic atomising nozzles in pesticide spraying and the influence of its spraying parameters on the deposition performance, this paper investigates the distribution of droplet size and the droplet deposition on corn seedlings by hydrodynamic nozzles under different operating parameters through experimental means, with a view to providing a reference to the research of hydrodynamic nozzles in the application technology, and to promote the technology in the agricultural plant protection operation. The results of this study are summarised as follows.

MATERIALS AND METHODS

Test equipment

The test was carried out in the atomisation laboratory of Shandong University of Technology, and the nozzle used was a hydrodynamic ultrasonic atomisation nozzle, which has the shape and parameters as shown in Fig. 1(a) and 1(b). A is the gas entry point, i.e. the input air pressure, and B is the liquid entry point; Peristaltic pump (XA01, input voltage 12V-24V, Changzhou)；Laser particle size analyser (Omeco, DP-02, Beijing, China); Adjustable DC Regulated Power Supply (Myson, MS305D, Guangdong Province); High-speed camera (PHOTRON, AX100-8G, Japan); Air compressor (DA5001, measuring output range 0-0.5MPa, Zhejiang).



(a) Nozzle model drawing (b) Nozzle parameter diagram

Fig. 1 - Ultrasonic atomizing nozzle

Experimental design

The test is divided into three parts, respectively, for different spraying conditions under the atomisation angle measurement test, droplet size test, droplet deposition test on corn seedlings, each test using its own control test method. Firstly, test the peristaltic pump to determine the volumetric flow rates produced under different input voltages. It is observed that the peristaltic pump operates effectively at an input current of 0.4A and an input voltage of 12V. However, it fails to function when the current or voltage drops below this threshold. To ensure proper operation of the peristaltic pump, maintain a fixed current of 0.4A during testing.

Fogging Atomisation angle test, droplet particle size test, and maize seedling deposition test were designed separately.

(1) *Atomisation angle test*

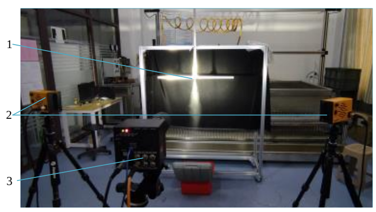
Atomisation angle measurement test used high-speed camera shooting, nozzle height from the ground 1500 mm, high-speed camera from the atomisation nozzle 2000 mm. The test was carried out indoors and there was indoor dark light treatment, in order to improve the shooting effect of high-speed digital camera. The test site is shown in Fig. 2(a). The test was conducted by adjusting the peristaltic pump input voltage to regulate the water intake of the ultrasonic atomising nozzle, and adjusting the output air pressure of the air compressor to regulate the input air pressure of the ultrasonic atomising nozzle. The gas pressure of the input gas was gradually increased from 0.1 MPa to 0.4M Pa at intervals of 0.1 MPa, and the fog shape sprayed from the atomising nozzle was photographed and recorded each time. The test results were analysed uniformly at a later stage and the corresponding conclusions were drawn.

(2) *Droplet size test*

Droplet particle size is one of the key factors affecting pesticide drift and settling. Under the condition of the same spray volume, the finer the droplet size, the higher the number of droplets, the more uniformly distributed on the target and the larger the coverage area. *Ding S.M. et al.* pointed out that it is a close factor affecting the value of spray droplet size. The nozzle used in this experiment is a hydrodynamic ultrasonic atomising nozzle, which requires a certain gas pressure and a certain amount of water intake in order to produce droplets, so in the droplet size test, a low intake volume of 500 mL/min was chosen, the gas pressure from 0.1 MPa to 0.4 MPa gradually increasing, the pressure interval of 0.1 MPa, ultrasonic atomising nozzle and the laser beam of the laser particle sizing instrument. The distance between the ultrasonic atomising nozzle and the laser beam of the laser particle sizer was gradually increased from 100 mm to 500 mm, and the size of the droplets under each gas pressure was measured using the laser particle sizer and the corresponding conclusions were drawn, and the droplet size detection system is shown in Fig. 2(b).

(3) *Maize seedling deposition test*

In order to investigate how effective ultrasonic atomising nozzles are in practical application in agriculture, this experiment was conducted using maize seedlings at the four to six leaf stage, with water-sensitive test strips placed at the tips, middle and roots of the broad upper and lower leaves of the maize on the seedlings. Corn seedlings were placed according to the standard corn field, row spacing of 600 mm, plant spacing of 250 mm, the test for the simulation of real corn field application scenarios, the ultrasonic atomisation nozzle is fixed in a certain speed of uniform movement of the trolley, ultrasonic atomisation nozzle distance from the crop canopy is 500 mm, the trolley travelling speed is set at 4.3 Km/h, select the low feed volume of 500 mL/min, before the start of each test until the fog pattern is stable, the test variable is the gas input pressure, the input pressure from 0.1 MPa gradually increasing to 0.4 MPa at intervals of 0.1 MPa. Before the start of each test, the robot moves forward at a constant speed after the fog is stabilised, the test variable is the input pressure of the gas, the input pressure gradually increases from 0.1 MPa to 0.4 MPa, with an interval of 0.1 MPa, and the water-sensitive test paper is replaced at the same position after each spraying in the next test, and after each test, the water-sensitive test paper is removed and placed in a standby position, and the test scenario is shown in Fig. 2(c), and all the tests are completed later. After all the tests were done, the water-sensitive test paper was analysed and the corresponding conclusions were drawn.



(a)Atomization Angle measurement system

(b)Droplet particle size detection system

(c)Droplet Deposition Test System

Fig. 2- Test site map

1. Ultrasonic atomizing nozzle；2. Fill light；3. Air compressor;4. Air compressor; 5. Peristaltic pump; 6. Laser particle size analyser 7. Water sensitive test paper; 8. Corn seedlings; 9 Sports car

RESULTS AND ANALYSES

The test results of the peristaltic pump in terms of the feed volume it can provide at different input voltages are shown in Table 1.

Table 1

Values of flow rates available for peristaltic pumps at different input voltages

Input Voltage	Input Current	Flow rate	Input Voltage	Input Current	Flow rate
V	A	mL·min^{-1}	V	A	mL·min^{-1}
12	0.4	450	19	0.4	750
13	0.4	500	20	0.4	800
14	0.4	550	21	0.4	850
15	0.4	600	22	0.4	870
16	0.4	650	23	0.4	900
17	0.4	700	24	0.4	950
18	0.4	720			

Size of atomisation angle under different spraying conditions

Test results

Under different experimental conditions, the test results of the atomization angle of the fluid dynamic ultrasonic atomizer nozzle are shown in Table 2. The experimental results can provide a basis for selecting different spraying schemes. Calibration of the atomisation angle is calculated by taking a picture of the stable fog pattern at the same height of the tip of the nozzle; drawing a horizontal reference line at a distance of 250 mm from the nozzle outlet, obtaining two intersections between the reference line and the atomisation boundary, and connecting the two points and the centre of the nozzle outlet to the angle obtained as the atomisation angle of the spray application, which is the conditional atomisation angle.

Table 2

Results of atomization angle test under different test conditions

Input Air Pressure	Feed volume	Fogging angle	Input Air Pressure	Feed volume	Fogging angle
MPa	mL·min^{-1}	°	MPa	mL·min^{-1}	°
0.1	450	31.89	0.3	450	70.17
0.1	500	21.43	0.3	500	69.91
0.1	550	18.90	0.3	550	70.29
0.1	600	19.97	0.3	600	67.88
0.1	650	20.08	0.3	650	66.10
0.1	700	18.78	0.3	700	64.37
0.1	750	18.72	0.3	750	54.86
0.1	800	21.29	0.3	800	55.13
0.1	850	18.93	0.3	850	51.18
0.1	900	18.63	0.3	900	40.99
0.1	950	17.40	0.3	950	35.91
0.2	450	28.02	0.4	450	107.38
0.2	500	25.35	0.4	500	104.11
0.2	550	25.08	0.4	550	90.98
0.2	600	24.83	0.4	600	89.75
0.2	650	23.48	0.4	650	77.87
0.2	700	24.51	0.4	700	72.27
0.2	750	24.17	0.4	750	54.32
0.2	800	23.73	0.4	800	46.12
0.2	850	23.54	0.4	850	45.32
0.2	900	23.20	0.4	900	43.2
0.2	950	22.22	0.4	950	42.70

Analysis of results

In order to more intuitively analyse the influence of the input air pressure and the liquid feed volume on the size of the atomization angle, establish a binary function with the input air pressure and the liquid feed volume as the independent variables, and the atomization angle as the dependent variable, and then use Origin2019 to plot the spatial surface distribution of the influence of the input air pressure and the liquid feed volume on the atomization angle, as shown in Fig.3.

As can be seen from Fig. 3, the atomization angle increases significantly with the increase of input air pressure at low inlet volume, which is due to the fact that the increase of input air pressure accelerates the impact of high-speed gas flow on the liquid stream broken, resulting in greater droplet dispersion force and gas shear force, which makes the liquid droplets to form more fine droplets, thus expanding the atomisation angle; at low input air pressures, the variation in liquid intake does not significantly alter the size of the atomization angle. This is because the lower pressure hinders the airflow from effectively dispersing the liquid into smaller droplets, resulting in shorter distances traveled by the droplets during the spraying process and a reduced level of collision and breakup. Larger droplets are more stable and less prone to further dispersion under low pressure, thus maintaining their shape and leading to a smaller atomization angle.

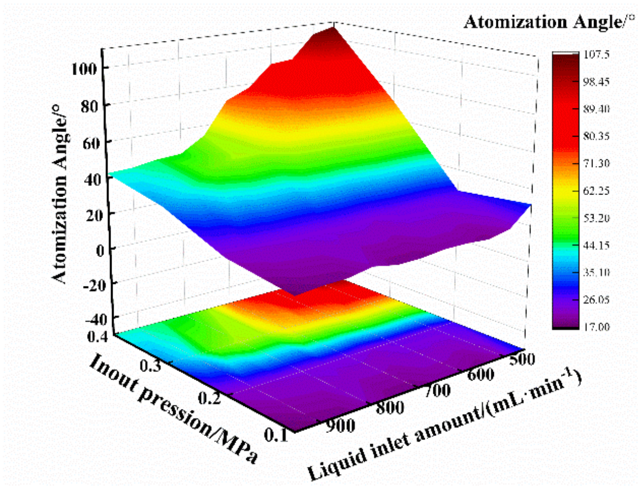


Fig. 3 - Atomization Angle diagram under different test conditions

Fitting of atomisation angle data under different spraying conditions

In order to further analyse the accuracy and reference value of the experimental data, Origin2019 was used to fit the polynomials to the atomisation angle data under different spraying conditions using the nonlinear surface fitting function, and the fitted model was Equation 1, where *x* represents the input air pressure, *y* represents the liquid inlet volume, *z* represents the atomisation angle, z_0 represents the zero offset, and A_i and B_i are the coefficients of *x* and *y*, respectively (i=1, 2, ⋯⋯5). Table 3 shows the parameters of the fitted model for the atomisation angle, the coefficient of determination R^2 for the polynomial fit is 0.85 and the Adjusted R^2 for the adjusted coefficient of determination is 0.81, which indicates that the fitted function is meaningful.

$$z = z_0 + A_1 \bullet X + A_2 \bullet pow(x,2) + A_3 \bullet pow(x,3) + A_4 \bullet pow(x,4) + A_5 \bullet pow(x,5) + \\ B_1 y + B_2 \bullet pow(y,2) + B_3 \bullet pow(y,3) + B_4 \bullet pow(y,4) + B_5 \bullet pow(y,5) \tag{1}$$

Table 3

Polynomial fitting model parameters

Parameters	z_0	A_1	A_2	A_3	A_4	A_5	B_1	B_2	B_3	B_4	B_5
Value	5.84	-1.11	6.32	-8.96	-1.96	4.39	-14.19	0.04	-6.02E-5	4.28E-8	-1.19E-11
Error	4．9E+6	1.29	1.07	2.03E9	-	-	38.72	0.12	1.71E-4	1.24E-7	3.53E-11

Droplet size under different spraying conditions

Test results

The droplet size value is the average value of 3 tests of the droplet size in each position of the axial direction of the ultrasonic atomising nozzle under different air pressures, and the results of the droplet size distribution tests with different input air pressures and different heights are shown in Table 4, which provides a basis for selecting the optimal input air pressures and optimal spraying heights of the fluid-dynamic ultrasonic atomising nozzles through the test results.

Table 4

Test results of droplet size under different spraying conditions

Input Air Pressure	Distance	Droplet size	Input Air Pressure	Distance	Droplet size
MPa	mm	μm	MPa	mm	μm
0.1	100	35.79	0.3	100	26.09
0.1	200	40.73	0.3	200	27.35
0.1	300	43.44	0.3	300	29.15
0.1	400	45.82	0.3	400	30.87
0.1	500	51.86	0.3	500	32.64
0.2	100	28.38	0.4	100	24.69
0.2	200	32.35	0.4	200	24.54
0.2	300	33.77	0.4	300	25.20
0.2	400	35.07	0.4	400	25.44
0.2	500	37.08	0.4	500	25.75

Analysis of results

It can be seen from Fig. 4 that the droplet particle size decreases significantly with the increase of input air pressure at a certain spraying height, and the droplet particle size increases with the increase of spraying distance at a certain input air pressure.

(1) Effect of Input Air Pressure on Droplet Size Distribution

As can be seen from Figure 4, the droplet size decreases significantly with the increase of air pressure. With the increase of the input air pressure, the speed of the airflow will be larger and larger, the impact on the liquid will be stronger, making it easier for the liquid to rupture the formation of smaller droplets, but the droplet size increases gradually with the axial distance. The larger the inlet air pressure, the droplet size in the axial position of the degree of change of the droplet size is smaller, and the distribution of the droplets is also more stable.

(2) Influence of different heights on droplet size distribution

As can be seen from Fig. 4, when the spraying air pressure is certain, with the spraying height increasing, the size of the droplet size is gradually increasing, this is because the farther away from the ultrasonic atomisation nozzle, the droplets themselves have a greater loss of kinetic energy, so the farther away from the nozzle the droplet condensation occurs, resulting in the droplet size of the droplet group increases.

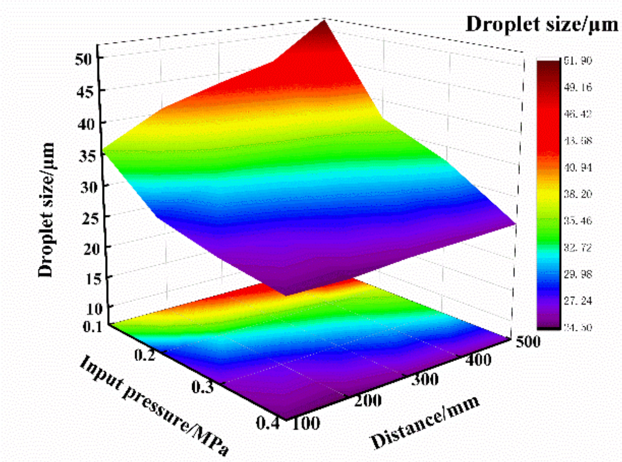


Fig. 4 - Particle size of droplets under different test conditions

Fitting of droplet size under different spraying conditions

In order to visually analyse the variation of droplet size, the polynomial fitting of the droplet size values under different spraying conditions was performed with reference to the data fitting method in the above chapters, and the fitting model was Eq. (2), in which x' indicated the input air pressure, y' indicated the spraying height, and z' indicated the atomization angle, z_0' denotes the zero offset, A′ and B′ are the coefficients of x' and y', respectively. Table 5 shows the parameters of the droplet size fitting model, and the coefficient of determination of the polynomial fit, R^2, is 0.94, and the adjusted coefficient of determination, Adjusted R^2, is 0.94. Adjusted R^2 is 0.88, which indicates that the fitting function is meaningful.

$$z' = z_0' + A_1' \cdot x' + A_2' \cdot pow(x',2) + A_3' \cdot pow(x',3) + A_4' \cdot pow(x',4) + A_5' \cdot pow(x',5) + B_1' y' + B_2' \cdot pow(y',2) + B_3' \cdot pow(y',3) + B_4' \cdot pow(y',4) + B_5' \cdot pow(y',5) \quad (2)$$

Table 5

Polynomial fitting model parameters

Parameters	z_0'	A_1'	A_2'	A_3'	A_4'	A_5'	B_1'	B_2'	B_3'	B_4'	B_5'
Value	-5.79E14	1.04E16	-5.06E16	4.48E15	4.35E17	-6.77E17	0.62	0.004	1.45E-5	-2.27E-8	1.34E-11
Error	4.81E6	6.58E7	4.6E8	7.69E8	-	-	5.31E4	4.36E2	1.65	0.002	1.93E-6

Evaluation of droplet deposition characteristics under different spraying conditions

Test results

The results of the droplet deposition measurements under different input air pressures are shown in Table 6, through which the test results can be verified for the pre-selected spraying conditions.

Table 6

Results of depositional coverage at each position of upper and lower leaves of maize

Placement	Input Air Pressure	Sedimentation coverage	Placement	Input Air Pressure	Sedimentation coverage
	MPa	%		MPa	%
tip of the upper leaf blade	0.1	10.41	tip of the lower leaf blade	0.1	11.60
	0.2	28.26		0.2	17.89
	0.3	35.60		0.3	22.75
	0.4	20.17		0.4	13.41
middle portion of the upper leaf blade	0.1	27.30	middle portion of the lower leaf blade	0.1	24.55
	0.2	54.69		0.2	34.87
	0.3	86.98		0.3	46.97
	0.4	66.79		0.4	40.85
root base of the upper leaf blade	0.1	3.60	root base of the lower leaf blade	0.1	1.87
	0.2	8.26		0.2	7.07
	0.3	16.84		0.3	14.10
	0.4	11.59		0.4	6.73

Analysis of results

The variation patterns of fog droplet deposition coverage under different test conditions are shown in Fig. 5, and the highest density of deposition coverage was found in the leaf among all positions. In addition, the highest droplet deposition coverage was found at 0.3 MPa air pressure, while the same results were obtained regardless of the position at which the test was conducted. However, at 0.4 MPa air pressure, the droplet deposition coverage was, on the contrary, less than that at 0.3 MPa, a phenomenon that can be explained by the interference of the high-speed airflow on the corn leaves, which resulted in some of the droplets not being able to be fully deposited on the target surface.

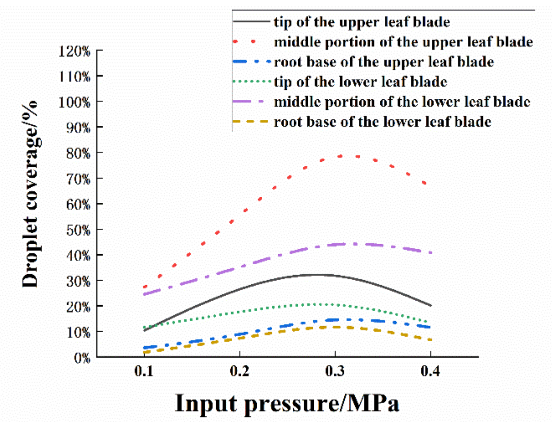


Fig. 5 - Results of droplet deposition coverage without test

CONCLUSIONS

(1) The atomisation angle will change with the change of input air pressure and liquid feed volume, in the liquid feed volume of 450 mL/min, the atomisation angle increases significantly with the increase of input air pressure, and the value of the angle of the atomisation angle ranges from 31.89° to 107.38°; in the input air pressure of 0.1 MPa, the value of the change of the size of the atomisation angle is not much affected by the change of the liquid feed volume, and the value of the change of the angle of the atomisation angle is only 14.49°.

(2) The change of input air pressure can obviously cause the change of droplet size, in the spraying height of 300 mm, the droplet size by the input air pressure size change value of 18.23 μm; in the input air pressure of 0.3 MPa, with the increase of spraying height, the droplet size will gradually become bigger, the droplet size change value of 4.78 μm, the further the distance from the nozzle, the droplets will be coagulated and phenomenon leads to the increase of the droplet size. The larger the distance from the nozzle, the more the droplets will be condensed, resulting in a large increase in droplet size.

(3) The potential of ultrasonic atomising nozzles in agriculture was explored through deposition test experiments on maize. The results show that the hydrodynamic ultrasonic atomising nozzle exhibits excellent deposition performance, with 86.98% of the middle part of the maize leaf being covered by a highspeed airflow, and 46.97% of the lower part of the maize leaf being covered by a leaf, resulting in a high deposition coverage. The results can provide a reference for the research of hydrodynamic nozzles in application technology and promote the in-depth application of this technology in agricultural plant protection operations.

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