# Nozzle test system for droplet deposition characteristics of orchard air-assisted sprayer and its application

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**Abstract:** In order to obtain nozzle droplet deposition characteristics for sprayer mechanical design and variable spraying control algorithms, a nozzle droplet deposition characteristics test system for air-assisted spraying was designed. The test system can supply a stable wind site with precisely controlled air speed whose speed control ranges from 2 m/s to 16 m/s with maximum relative error of 4.5%. It can spray out a certain amount of liquid pesticide with adjustable spraying pressure which can be controlled with high precision while the maximum relative error is only 1.33%. The distribution of droplet deposition can be collected and measured by using the acquisition device and a pesticide deposition optical measurement system. The experiment of two-dimensional nozzle flow measurement was carried out. The results show that nozzle flow distribution is uniform and symmetric with "double-hump" shape in the spray range. Multi-nozzle overlapped droplet deposition ranges from 85% to 116% relative to the average. The nozzle droplet deposition experiment was completed. The experiment results show that in air-assisted spraying, the higher the wind speed, the less droplet deposition is affected by gravity. When the wind speed is higher than 12 m/s and spraying distance is 0.80 m, droplet deposition is concentrated on the originally designated point and hardly affected by gravity. The horizontal spray width becomes smaller with higher wind speed. When the wind speed is high, it can be considered that nozzle deposition only focuses on the nozzle center, if the position requirement is not very high in orchard spraying.

**Keywords:** air-assisted spraying, orchard sprayer, flow distribution, droplet deposition, nozzle test system, characteristics test system

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## 1 Introduction

Pest and disease control is one of the most important issues in orchard management. According to statistics, the workload of pest and disease control is about 30% of the total workload of orchard management[1,2]. Spraying quality and effectiveness will directly affect fruit safety, quantity and quality of production and management costs[3-7]. Orchard air-assisted spraying is an advanced and efficient application technique which is recommended by the FAO. The droplets are blown into the fruit tree canopy by the forced air, which can

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effectively resist the natural wind disturbance and reduce spraying drift to decrease pesticide environmental pollution[8-12].

Deposition characteristics, which mostly determine the spraying quality, are used to evaluate the performance of the sprayer[13,14]. The results of deposition characteristics research are an important reference for sprayer optimization[15-17]. The single nozzle deposition characteristics experiment is the basis of sprayer deposition characteristics research. In the process of sprayer mechanical design, nozzles arrangement needs the data support of single nozzle deposition characteristics; and single nozzle deposition characteristics play more important roles in individual nozzle flow control algorithm and wind speed regulation algorithm design.

The objective of this study was to obtain nozzle droplet deposition characteristics through experiments for sprayer mechanical and variable spraying control algorithms design, by using the nozzle test system designed for droplet deposition characteristics.

## 2 Materials and methods

### 2.1 Air-assisted spraying control and nozzle droplet acquisition system design

In order to experimentally research nozzle droplet deposition characteristics, an air-assisted spraying control and nozzle droplet acquisition system was developed. The system consists of an air delivery module, a pesticide spraying module and a droplet deposition acquisition device. The air delivery module can supply a stable wind site with wind speed precisely controlled. The pesticide spraying module can spray out a certain amount of liquid pesticide with adjustable spraying pressure. The droplet deposition acquisition device was used to acquire nozzle droplet by using fixed filter papers.

#### 2.1.1 Air delivery module

The air delivery module includes a fan (YDW0.55-6, Foshan Nanhai Jiuzhou Popula Fan Co., Ltd., Guangdong, China), an air pipe, a frequency converter (OPI900, Shopin Electric Co., Ltd., Shanghai, China) and a computer (Figure 1). After wind speed is set by the user, the PC software which is running in the computer calculates the frequency needed and sends control commands to the frequency converter through an RS485 serial port. The frequency converter controls the rotation speed of the fan to adjust the wind speed by changing its output frequency. The fan has a three-phase asynchronous motor with 380 V input and 550 W output. The input and output voltages of the frequency converter are 220 V and 380 V respectively.

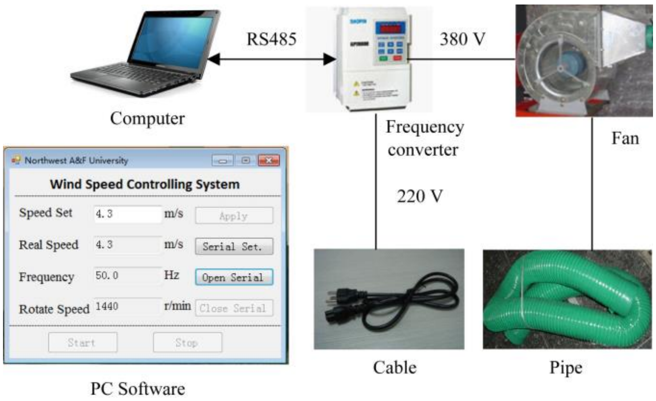



Figure 1 Schematic diagram of air delivery module

The PC software was used to calculate the frequency according to the relationship equation between wind speed and frequency which was experimentally obtained. The output frequency of the frequency converter was set from 5 Hz to 50 Hz with steps of 5 Hz. Then the wind speed was measured three times at each frequency by using an anemometer (A531-01449, Kanomax Japan Inc., Osaka, Japan), and the average wind speeds were calculated (Figure 2). A linear equation was obtained and the $R^2$ of the equation is 0.9998.

$$y = 0.3106x$$

where, $y$ is wind speed in m/s; $x$ is output frequency of frequency converter in Hz.

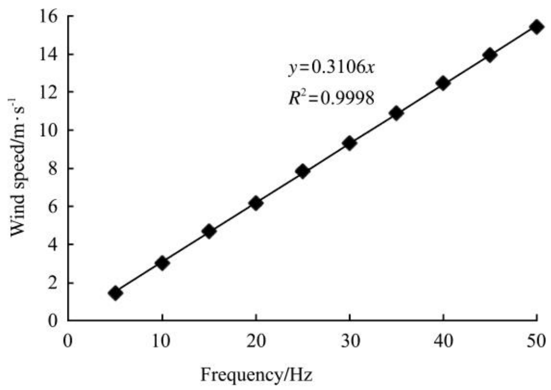



Figure 2 Relationship equation between wind speed and output frequency of converter

The PC software communicates with the frequency converter through an RS485 serial port. There are Serial Set, Open Serial and Close Serial - three buttons - for serial port setting and operation (Figure 1). The real-time frequency of the converter and the rotation speed are shown to the user. And the real wind speed is calculated and shown according to the linear equation obtained. The wind speed can be changed by the user by inputting the new speed value to the Speed Set textbox and pressing the Apply button.

2.1.2 Pesticide spraying module

The pesticide spraying module is composed of a pesticide liquid supply component and a spraying pressure control component (Figure 3). The former component consists of an air pump, an air tank, a pesticide bottle, pipes, a solenoid valve and a nozzle. Air under pressure, which is generated by the air pump, goes through pipes, the PID pressure regulating valve and the air tank into the pesticide bottle. The liquid in the bottle was pressed out of the nozzle through pipes and the solenoid valve. The spraying pressure control component includes a pressure controller, a PID pressure regulating valve (MPPE-3-1/ 8-6-420-B, Festo corporate company, Germany) and a pressure sensor (AST4100, American Sensor Technologies Inc., USA). The pressure controller collects pressure information from the sensor, displays the pressure value and in real-time adjusts the PID pressure regulating valve to keep the air tank pressure stable at the pressure set by the user.

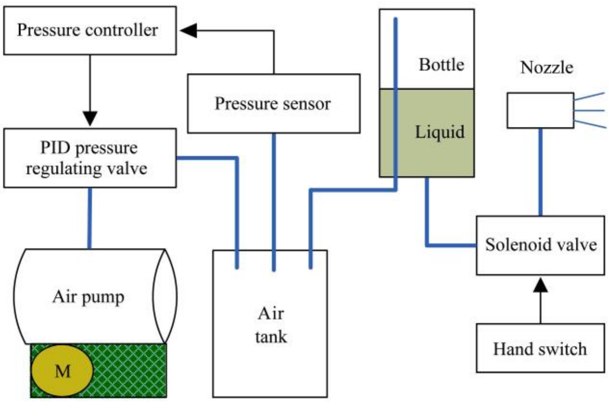



Figure 3 Schematic diagram of pesticide spraying module

2.1.3 Deposition acquisition device

The deposition acquisition device with 3.2 m in height and 1.2 m in width was developed (Figure 4). There are 8 grids each sized 1.2 m by 0.4 m installed on the vertical bars. It is easy to affix and remove filter papers on the grids. The filter papers can absorb liquid spraying tracer.

The air-assisted spraying control and nozzle droplet acquisition system was developed as shown in Figure 4.

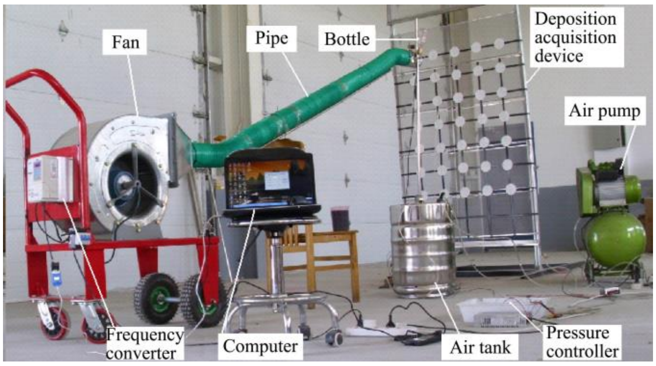



Figure 4 Air-assisted spraying control and nozzle droplet acquisition system

## 2.2 Square two-dimensional nozzle flow measurement device

Nozzle flow distribution is a very important factor to consider when designing the arrangement of sprayer nozzles. In order to measure nozzle flow two-dimensional distribution easily, a square two-dimensional nozzle flow measurement device was designed. The square device is 0.470 m in length, 0.470 m in width and 0.040 m in height, in which there are 21 square lattices on each side with 441 square lattices totally. A square lattice is 0.020 m in length, 0.020 m in width and 0.035 m in depth, and the volume of each lattice is 0.014 L (Figure 5).

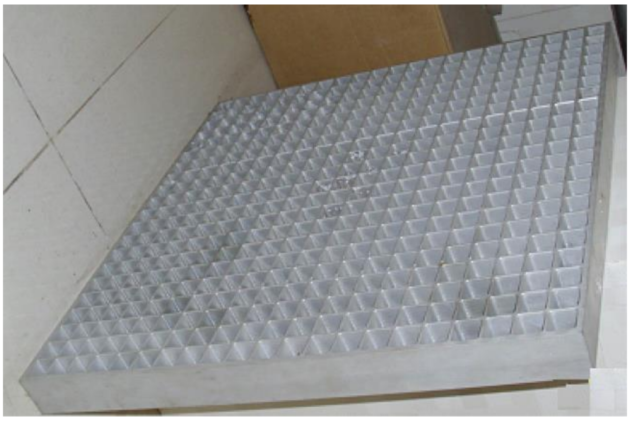


Figure 5 Square two-dimensional nozzle flow measurement device

## 2.3 Optical measurement device of pesticide deposition

In spraying pesticide deposition trials, instead of pesticide, tracer was used which was captured by filter paper. After the tracer was washed off from filter paper by using a known amount of distilled water, its quantity can be measured by the optical deposition measurement device. Then the tracer solution volume sprayed to the target can be calculated. The optical deposition measurement device used in this study is shown in Figure 6. There are an auto sampler, a solute concentration optical measuring instrument and a computer (three parts). The auto sampler can absorb the tracer solution sample automatically in order. The optical measuring instrument meters the tracer solute concentration and sends the resulting data to the computer. The computer can calculate and record the concentration and can print the report form by using software Visionlite Quant (Thermo Fisher Scientific Inc, USA).

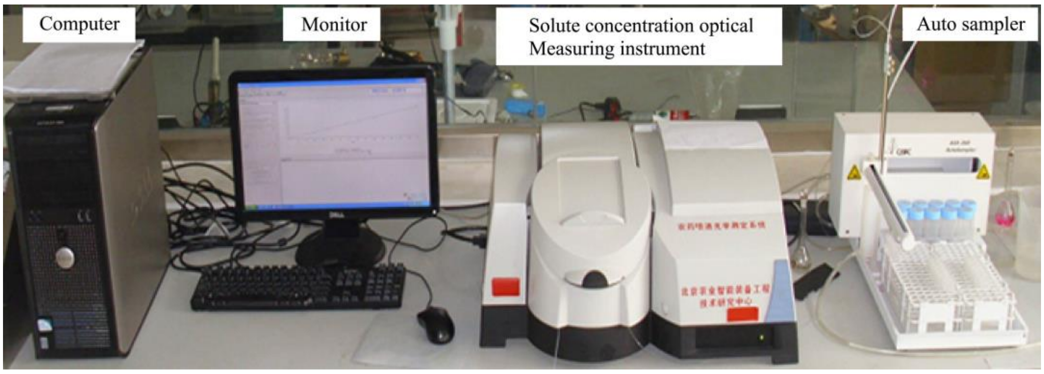



Figure 6 Optical measurement device of pesticide deposition

## 3 Experiments

The experiments were carried on in National Engineering Research Centre for Information Technology in Agriculture in Beijing China in June 2012. All the experiments were done in a workshop, where the surrounding air speed is 0 with normal temperature of about 25 ℃.

### 3.1 Wind speed control precision test

In order to test the effectiveness of the air delivery module, a wind speed control precision test was done. Wind speed was set at one certain value from 2 m/s to 16 m/s with steps of 2 m/s by using the PC software. At each wind speed setting, the real wind speed at the air pipe outlet was measured three times by using an anemometer (A531-01449, Kanomax Japan, Inc., Osaka, Japan). The test results show that the precision of wind speed control is high while the maximum relative error is 4.5%.

### 3.2 Spraying pressure control precision test

Spraying pressure was set at one certain value from 0.20 MPa to 0.55 MPa with steps of 0.05 MPa by using the pressure controller (Table 2). In Table 2, Pressure Set value is the user input value, while Real Pressure value is from the pressure sensor. The test results show that the spraying pressure can be controlled well with high precision while the maximum relative error is only 1.33%.

**Table 1 Results of wind speed control precision test**

| Wind speed set /m $s^{-1}$ | Wind speed measured/m $s^{-1}$ | | | | Relative error /% |
|---|---|---|---|---|---|
| | value 1 | value 2 | value 3 | Average | |
| 2 | 1.92 | 1.90 | 1.91 | 1.91 | 4.50 |
| 4 | 3.87 | 3.84 | 3.91 | 3.87 | 3.17 |
| 6 | 5.74 | 5.95 | 5.98 | 5.89 | 1.83 |
| 8 | 7.85 | 8.04 | 8.02 | 7.97 | 0.38 |
| 10 | 9.89 | 10.1 | 9.87 | 9.95 | 0.47 |
| 12 | 11.9 | 12.3 | 12.1 | 12.1 | 0.83 |
| 14 | 13.9 | 14.4 | 14.3 | 14.2 | 1.43 |
| 16 | 16.1 | 16.3 | 16.4 | 16.3 | 1.67 |

**Table 2 Results of spraying pressure control precision test**

| Pressure set/MPa | Real pressure/MPa | Relative error/% |
|---|---|---|
| 0.200 | 0.202 | 1.00 |
| 0.250 | 0.253 | 1.20 |
| 0.300 | 0.304 | 1.33 |
| 0.350 | 0.348 | 0.57 |
| 0.400 | 0.402 | 0.50 |
| 0.450 | 0.447 | 0.67 |
| 0.500 | 0.498 | 0.40 |
| 0.550 | 0.549 | 0.18 |

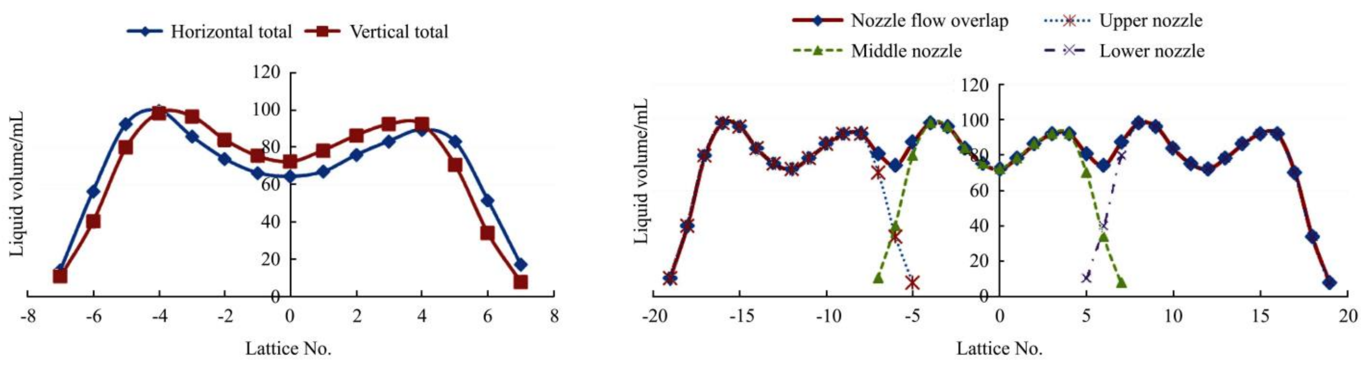
### 3.3 Two-dimensional nozzle flow distribution measurement experiment

Two-dimensional flow distribution of the TEEJET

AITXA 8002 nozzle was measured by using the square nozzle flow measurement device. The nozzle was fixed 0.20 m higher above the center of the device. Pesticide liquid was continuously vertically downward sprayed to the device for 80.23 s with spraying pressure 0.3 MPa. The flow distribution is shown in Table 3 in which the number of the center square lattice is 0. The horizontal and vertical sum statistics of the flow distribution were respectively done (Figure 7a). The horizontal and vertical sum statistical results show that when the nozzle height is 0.20 m the spraying width is about 12 square lattices wide (0.24 m). The curves of horizontal and vertical sum statistics are similar. Both nozzle flow distribution curves are uniform and symmetric with "double-hump" shape in the spray range. If nozzles are arranged 0.24 m apart away to make the distance of nozzles and spraying width the same, the flow distribution of nozzles will be overlapped by single nozzle flow distribution. Take vertical sum statistics, for example. The overlapped flow distribution result is shown in Figure 7b. Liquid volume in each lattice ranges from 72.3 mL to 98.4 mL with average volume 84.9 mL, standard deviation 9.26. Flow distribution ranges from 85% to 116% relative to the average.

**Table 3 Results of nozzle two-dimensional flow distribution measurement**

| Square lattice No. | Liquid volume/mL | | | | | | | | | | | | | | | Horizontal total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | -7 | -6 | -5 | -4 | -3 | -2 | -1 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
| -7 | 0 | 0 | 0 | 0 | 0.8 | 1.6 | 2.4 | 3 | 3.3 | 1.8 | 0.9 | 0 | 0 | 0 | 0 | 13.8 |
| -6 | 0 | 0 | 0 | 1.8 | 4 | 6.8 | 8.8 | 10 | 9.9 | 8.2 | 5 | 2 | 0 | 0 | 0 | 56.5 |
| -5 | 0 | 0 | 1.9 | 5.2 | 8.9 | 10.6 | 11 | 11.6 | 12 | 12.4 | 10.08 | 6.5 | 2.3 | 0 | 0 | 92.48 |
| -4 | 0 | 1.6 | 5.1 | 9.4 | 11.2 | 9.2 | 7.5 | 7 | 8.3 | 10 | 12 | 11 | 5.4 | 1.9 | 0 | 99.6 |
| -3 | 0.8 | 3.3 | 7.8 | 10.2 | 8.6 | 5.9 | 4.1 | 3.5 | 4.2 | 6.2 | 8.6 | 10.8 | 8.4 | 3.3 | 0 | 85.7 |
| -2 | 1.2 | 4.8 | 9.1 | 9 | 6.2 | 3.7 | 1.9 | 1.4 | 1.9 | 3.5 | 6.2 | 9.3 | 9.3 | 5 | 1.3 | 73.8 |
| -1 | 1.5 | 5.9 | 9.3 | 8.1 | 4.7 | 2.1 | 1 | 0 | 1 | 3 | 5 | 8.3 | 9 | 5.8 | 1.5 | 66.2 |
| 0 | 2.6 | 6.4 | 9.6 | 7.9 | 4.5 | 1.8 | 0 | 0 | 0.8 | 2.2 | 4.8 | 7.4 | 8.7 | 5.6 | 2 | 64.3 |
| 1 | 1.7 | 6.3 | 10 | 8.6 | 5 | 2.5 | 1.1 | 0 | 1.4 | 2.8 | 5.1 | 7.5 | 8.1 | 5 | 1.8 | 66.9 |
| 2 | 1.8 | 5.7 | 9.9 | 9.3 | 7 | 4 | 2.7 | 2.4 | 3 | 4.3 | 6.2 | 7.8 | 7.4 | 3.2 | 1.2 | 75.9 |
| 3 | 1 | 3.7 | 8.6 | 10.3 | 8.6 | 6.4 | 4.8 | 4.5 | 5 | 6.3 | 7.6 | 7.9 | 5.8 | 2.8 | 0 | 83.3 |
| 4 | 0 | 1.8 | 5.9 | 9.4 | 10.6 | 9.4 | 7.7 | 7.4 | 7.7 | 8.4 | 8.6 | 7 | 4.1 | 1.4 | 0 | 89.4 |
| 5 | 0 | 0.8 | 2.6 | 6.4 | 9.9 | 10.4 | 10.2 | 9.8 | 9.7 | 9 | 7.3 | 4.8 | 2 | 0 | 0 | 82.9 |
| 6 | 0 | 0 | 0 | 2.8 | 5.4 | 7.3 | 8.5 | 8.4 | 7.3 | 6 | 3.8 | 2 | 0 | 0 | 0 | 51.5 |
| 7 | 0 | 0 | 0 | 0 | 1.2 | 2.4 | 3.6 | 3.3 | 2.9 | 2.3 | 1.2 | 0 | 0 | 0 | 0 | 16.9 |
| Vertical total | 10.6 | 40.3 | 79.8 | 98.4 | 96.6 | 84.1 | 75.3 | 72.3 | 78.4 | 86.4 | 92.38 | 92.3 | 70.5 | 34 | 7.8 | |




a. Single nozzle flow distribution statistics

b. Nozzle flow overlapped distribution statistics

Figure 7 Statistical results of nozzle flow distribution

### 3.4 Spraying deposition optical measurement recovery ratio test

In spraying pesticide deposition trials, dilute solution of Rhodamine tracer was sprayed and captured by filter paper with diameter of 0.09 m (Hangzhou Special Paper Industry Co., LTD., China). The tracer was washed off from the filter paper by using a known amount of water to obtain sample solution. But there will be a certain amount of tracer residue on the filter paper which will affect the test result. In order to accurately calculate the amount of tracer on the filter paper, a tracer deposition recovery ratio is needed. To obtain the recovery ratio, a spraying deposition optical measurement recovery ratio test was done. Firstly, 0.5 mL original Rhodamine was directly diluted to 50 mL solution by using distilled water. Secondly, 0.5 mL original Rhodamine was dropped on the filter paper, then the tracer was washed off and diluted to 50 mL solution. Finally, the two solution samples were measured by using the optical measurement device. The test was repeated three times (Table 2). The test results show that the recovery ratios of different recovery solutions are almost the same. And the average recovery rate is 83.78%.

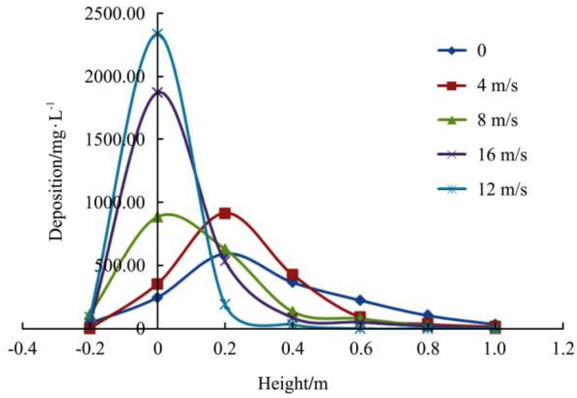
**Table 4 Test results of recovery ratio**

| Test | Concentration/mg·L$^{-1}$ | | | | Recovery ratio/% |
|---|---|---|---|---|---|
| | Value 1 | Value 2 | Value 3 | Average | |
| Original solution | 55.65 | 55.64 | 56.52 | 55.94 | |
| Recovery solution 1 | 46.53 | 47.42 | 47.11 | 47.02 | 84.06 |
| Recovery solution 2 | 47.12 | 46.9 | 46.55 | 46.86 | 83.77 |
| Recovery solution 3 | 46.35 | 47.08 | 46.69 | 46.71 | 83.50 |

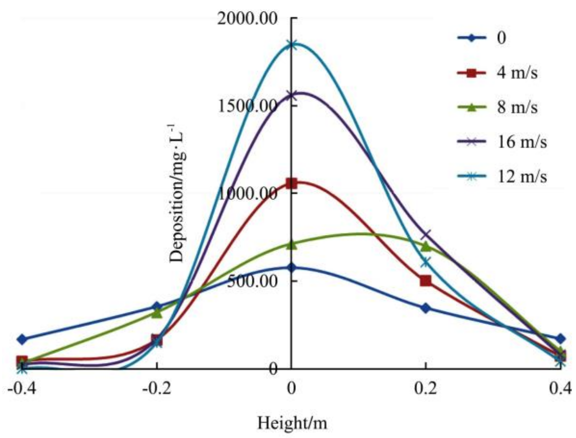
### 3.5 Nozzle droplet deposition test

Nozzle deposition characteristics tests were done at different wind speeds by using the deposition characteristics test system developed. On the deposition acquisition device, there were 35 pieces of filter paper fixed on each of the cross points of a 7 rows × 5 columns area (Figure 4). Both row width and column width were 0.2 m. The bottom row was 0.7 m in height from the ground. The row 1.7 m in height was defined as abscissa axis whose positive direction is left, while middle column is vertical coordinates with downward positive direction. The nozzle which vertically pointed to origin of coordinates was fixed 0.80 m away from the acquisition device. The spraying pressure was 0.3 MPa. Tracer Rhodamine 45 mL was added into about 1 000 mL distilled water to make the original solution for the test. Original solution 5 mL was taken out and 200-fold diluted with distilled water. The concentration of the dilute solution was measured three times whose values were 214.60, 212.97 and 213.07 mg/L with an average value 213.55 mg/L. Therefore the concentration of the original solution was 42.71 g/L.

New filter papers were fixed on the deposition acquisition device. The liquid bottle was filled with 20 mL original solution. The fan was turned off to create a wind speed of 0. After spraying out the original solution tracer, all pieces of filter paper were taken off and stored in the light-proof sample bottles immediately. The tracer on each piece of filter paper was washed off and diluted to 50 mL solution. The concentration of the dilute solution was measured. Then the wind speed was set to 4, 8, 12 and 16 m/s and the liquid bottle was filled of 15, 10, 5 and 5 mL, respectively. After each spraying, the content of tracer on filter paper was measured. If the volume of spraying solution was not 20 mL, the test results were converted based on the actual volume of tracer sprayed. For example, if the actual spraying volume is 10 mL, the test result will be multiplied by 2 in order to facilitate comparison to the spraying volume of 20 mL. Deposition results at different positions and different wind speeds are shown in Figure 8.




a. Deposition at different heights




b. Deposition at different horizontal widths

Figure 8 Effects of wind speed on droplet deposition at different positions

The tests results in Figure 8a show that the higher the wind speed is, the more droplet deposition is influenced by gravity and the lower the distribution is. On the other hand, the higher the wind speed is, the less droplet deposition is affected by gravity and the more it focuses on the originally designated point. When the wind speed is higher than 12 m/s and spraying distance is 0.80 m, droplet deposition is hardly affected by gravity. Figure 8b shows that the spraying width also varies with wind speed. The horizontal spray width becomes smaller with higher wind speed.

## 4 Discussion

In China, the row width of most standard orchards such as apple, cherry and citrus orchards ranges from 4 m to 5 m. In mature orchards the distance between canopies in adjacent row is from about 1.5 m to 2.5 m. The width of the orchard sprayer is about 1 m. The distance from nozzles to canopy surface is generally not more than 0.8 m. The main aim of air-assisted spraying is to apply the pesticide into orchard tree canopy to improve the internal deposition. Before pesticide enters the tree canopy, the influence of gravity on the pesticide droplets should be reduced to decrease pesticide deposition on the soil[18,19]. According to experimental results in this paper, when the wind speed at nozzle position is more than 12 m/s and the spray distance is 0.80 m, deposition is hardly affected by gravity. It is recommended that wind speed should be more than 12 m/s.

In the process of sprayer research and development, arrangement of the nozzles, which determines deposition distribution to a certain extent, is very important[20,21]. Single nozzle flow distribution is an important basis of nozzle arrangement. Nozzle arrangement can be preliminarily determined according to nozzle flow distribution and the deposition requirement of the sprayer. If the flow distribution requirement of a vineyard sprayer is uniform, according to the test result in Figure 8a, nozzles can be preliminarily arranged 0.2 m apart from each other before fine-tuning correction.

Nozzle flow deposition distribution is the basis of single nozzle independent control especially in target-oriented spraying[22,23]. According to test results in Figure 8, if the wind speed is lower than 12 m/s, the distance droplets fall down should be calculated and a special control algorithm should be developed to solve this problem. Droplet deposition concentrates in the center of the nozzle spray width. When the wind speed is high, it can be considered that nozzle deposition only focuses on the nozzle center, if the position requirement is not very high in orchard spraying.

## 5 Conclusions

1) Nozzle droplet deposition characteristics test system was designed for air-assisted spraying test. It can supply a stable wind site with air speed precisely controlled whose speed control ranges from 2 m/s to 16 m/s with maximum relative error 4.5%. It can spray out a certain amount of liquid pesticide with adjustable spraying pressure which can be controlled with high precision while the maximum relative error is only 1.33%.

2) TEEJET AITXA 8002 nozzle flow distribution horizontal and vertical sum statistics are similar which are uniform and symmetric with “double-hump” shape in the spray range. Multi-nozzle overlapped droplet deposition ranges from 85% to 116% relative to the average.

3) In air-assisted spraying the smaller the wind speed is, the more droplet deposition is influenced by gravity and the lower the distribution is. When the wind speed is more than 12 m/s and spraying distance is 0.80 m, droplet deposition is concentrated on the originally designated point and hardly affected by gravity. It is recommended that wind speed at nozzle position should be higher than 12 m/s.

4) The horizontal spraying width also varies with wind speed. It becomes smaller with higher wind speed. When the wind speed is high, it can be considered that nozzle deposition only focuses on the nozzle center, if the position requirement is not very high in orchard spraying.

## Acknowledgements

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