Canopy deposition characteristics of different orchard pesticide dose models

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Abstract: Pesticide dose model based on canopy characteristics is the guidance basis for spray parameters adjustment. In this study, the calculation formula and canopy deposition characteristics of leaf wall area (LWA) model, tree row volume (TRV) model, and optimal coverage method (OCM) model were described and compared. A tower air-assisted spray test bench was applied to provide fine quality droplets, suitable wind speed and demand spray flow rate for corresponding models, an electric flat board vehicle was applied to drive tree in a straight line to simulate the sprayer movement speed, and droplet deposition distribution were tested in different leaf area density canopy. The results showed that the spray flow rates of three pesticide dose models decreased gradually. LWA model was only related to canopy height, TRV model was related to canopy height and canopy diameter, while OCM model was related to canopy height, canopy diameter and leaf area density. Whether dense or sparse canopy, TRV model basically satisfied the requirement of coverage rate greater than 33% in the entire canopy, OCM model met the requirement of coverage density greater than 70 droplets/cm^2. However, LWA model, for dense canopy, unit area deposition of outermost leaves near sprayer was 3.6 times of the apple leaf maximum retention, which had a high loss risk; for sparse canopy, penetration rates of outermost leaves far away sprayer, that is, the drift rate was 21.4%. The discussion leads to the conclusion that for conventional spraying, TRV model represented a substantial improvement compared to LWA model, and OCM model was a reasonable low volume spraying model. This study provides a reference to different growth seasons spray amount adjustments in orchard.

Keywords: orchard plant protection, pesticide dose model, leaf wall area, tree row volume, optimal coverage method

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1 Introduction

China's fruit tree cultivation area and fruit production increase year by year[1]. Fruit tree canopy parameter varies greatly from different growth periods, and fruit tree has a demand for spraying pesticides during sprouting period, flowering period, and fruit development period. Due to the lack of spray parameters adjustment guidance, pesticides waste and environmental pollution are serious. Plant protection workers usually use a fixed spray amount for different growth seasons, replace nozzles and adjust sprayer speed are the most commonly used adjustment methods[2].

The main factors affecting spray deposition includes fruit tree canopy structure characteristics and sprayer operation parameters. Canopy structure parameters include: height, width, volume, leaf area density. Sprayer operation parameters include: spray flow rate, spray droplet size, air volume, air speed, sprayer speed and spray distance. Cross et al. studied the impact of spray liquid flow rate[3], spray quality[4] and air volumetric flow rate[5] on apple canopy deposition distribution. Holterman et al.[6] studied the downwind drift characteristics of axial flow fan-assisted orchard sprayer, the consecutive function of BBCH growth cycle under different canopy density was established. Sun et al.[7] studied the effects of leaf area density and wind speed on droplet penetration, deposition and drift, the optimum wind speed of pear trees with different leaf area density was obtained. Wang et al.[8] studied the relational model between air flow velocity and canopy width, leaf area index and porosity rate. According to numerical simulation[9] and experimental research[10] of droplet deposition law, they have developed different application models.

Pesticide dose model based on canopy characteristics is the guidance basis for spray parameters adjustment[11,12]. At present, five pesticide dose calculation models have been developed: Ground Area (GA) model[13], Leaf Wall Area (LWA) model[14,15], Tree Row Volume (TRV) model[16], Optimal Coverage Method (OCM) model[17], General model[18]. The TRV model has been applied to variable spray systems based on ultrasonic sensor detection of tree diameter[19-21]. Some orchard dose adjustment decision support systems have been developed[22]. Xue et al.[23] obtained leaf wall area by using radar detection techniques, and proposed the pesticide dose calculation model based on the decision coefficient of K_{LWA}. Chen[24] pointed out that the decision coefficient value in the pesticide dose calculation model need to be further studied.

In summary, researchers have recognized the correlation between spray amount and canopy structure, and developed five pesticide dose models. However, the applicability and canopy deposition patterns of different pesticide dose models has not been compared and evaluated. In this study, the calculation formula and canopy deposition characteristics of LWA model, TRV model, and OCM model were described and compared, which was expected to

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provide a reference to different growth seasons spray amount adjustments and precise variable spray decision models in orchard.

2 Pesticide dose models

Among the five pesticide dose models, GA model is independent of the canopy structure, sprayer keeps constant dosage on different parameters fruit trees[13] while in General model, the self-defined coefficients such as canopy interception rate, cumulative interception rate and porosity[25,26] are difficult to determine. Therefore, the GA model and the General model are not within the scope of this article.

Under single-sided spray conditions, the demand spray amount calculate equations of LWA model, TRV model, and OCM model are as follows context:

2.1 LWA model

The leaf wall area per unit land area is calculated according to the canopy height and row spacing. According to GA model spray amount per hectare, the LWA model test area spray flow rate was calculated by Equation (1).

$$q_1 = \frac{60 Q_{GA} hRv}{2HS} \tag{1}$$

where, q_1 is LWA model spray flow rate, L/min; Q_{GA} is GA model spray amount per hectare, L/hm^2; h is the test area canopy height, m; R is row spacing, m; v is sprayer speed, m/s; H is average orchard canopy height, m; S is the orchard area, m^2.

2.2 TRV model

1 L of water is sufficient to wet 7.48 m^3 of leaf canopy volume[27]. In order to reduce pesticide drift, Sutton[27] proposed a correction coefficient in the range of 0.7 to 1.0 according to the fruit tree canopy density. Spray amount per unit canopy volume in this study was set as 0.1 L/m^3. The TRV model test area spray flow rate was calculated by Equation (2).

$$q_2 = 60r \cdot h \cdot v \cdot V_s \tag{2}$$

where, q_2 is TRV model spray flow rate, L/min; r is tree canopy radius, m; h is the test area canopy height, m; v is sprayer speed, m/s; V_s is the spray amount per unit canopy volume, 0.1 L/m^3.

2.3 OCM model

Pesticides have different optimal coverage densities due to different mechanisms of internal absorption or contact killing. At 200 μm reference droplet diameter, the optimal coverage density is 80 to 120 droplets/cm^2[28]. The optimal coverage density in this study was set as 100 droplets/cm^2. Leaf area density, referred to as L_{AD}, is leaf surface area per unit canopy volume. L_{AD} and canopy volume were applied to calculate OCM model spray flow rate of positive and negative leaves surface, as shown in Equation (3).

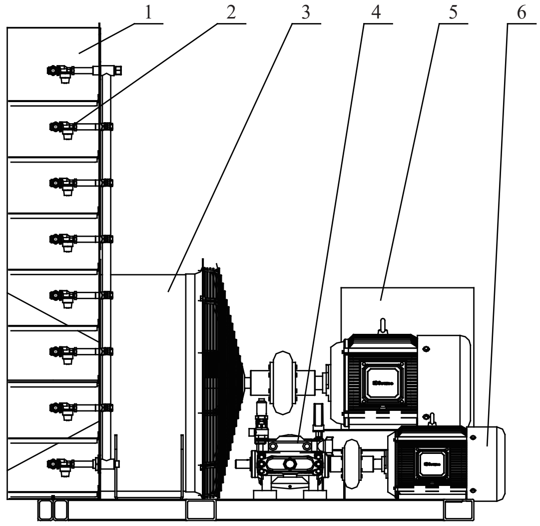
$$q_3 = 2 \times 60rhv L_{AD} D_i \cdot \frac{4}{3}\pi\left(\frac{\text{VMD}}{2}\right)^3 \times 10^{-11} \tag{3}$$

where, q_3 is the OCM model spray flow rate, L/min; r is the tree canopy radius, m; h is the test area canopy height, m; v is the sprayer speed, m/s; L_{AD} is the leaf area density value, m^2/m^3; D_i is the optimal coverage density, 100 droplets/cm^2; VMD is the reference droplet diameter, 200 μm.

3 Materials and methods

3.1 Tower air-assisted spray test bench

As shown in Figure 1, the tower air-assisted spray test bench was mainly composed of an axial fan, a tower airflow channel, a plunger pump, several nozzles, two three-phase asynchronous motors, two frequency converters and so on. The axial fan diameter was 660 mm with 9 blades, and rotation speed adjustment range was 0-3000 r/min. Tower airflow channel with a height of 1300 mm and a width of 160 mm. 3WZ-25 three cylinder plunger pump (Physics agriculture and Forestry Machinery Technology Co., Ltd.), with rotation speed of 430-850 r/min and flow rate of 7.5-15.5 L/min. Solid and hollow conical spray nozzles (Taizhou Xinyi Agricultural Machinery Co., Ltd, China), and the spray hole diameter of ceramic spray sheets were 0.8 mm, 1.0 mm, 1.2 mm, and 1.5 mm.



1. Tower airflow channel 2. Nozzle 3. Axial fan 4. Plunger pump 5. Control box 6. Motor

Figure 1 Tower air-assisted spray test stand

3.2 Test instruments and materials

Instruments and materials used in the test included: DP-02 laser particle sizer (OMEC Instrument Corporation, Zhuhai, Guangdong, China) with repetitive error <3%, test range 1-1500 μm; Lamellae vertical patternator with 5 m in height and 1.7 m in width; Pressure gauge (Shanghai Automation Instrument Corporation, China) with measurement range of 0-1.5 MPa and 0.4 accuracy grade; Hot wire anemometer (Kanomax Corporation, Japan) with measuring range of 0-50 m/s and accuracy ±2%; 9000F Mark II scanner (Canon, Japan); Water sensitive paper (Syngenta, Switzerland) with a size of 76 mm×26 mm; Kestrel 4500 Meteorological anemometer (Kestrel Corporation, USA) with a minimum sampling interval of 10 s; Fa2004 analytical balance with a measuring range of 200 g and accuracy of 0.0001 g; Double gantry manual stacker with a load capacity of 1000 kg and a maximum lifting height of 2 m; Electric flat board vehicle with a motor power of 800 W and load capacity 1000 kg; Sampling rod with a length of 1.4 m; and Universal clamps.

3.3 Test method

3.3.1 Leaf area density measurement

The tested tree was a 6-year-old potted white magnolia tree with a trunk diameter of 8 cm and a canopy diameter of 1.4 m. 100 leaves of non-test magnolia trees were randomly collected, and were scanned into pictures with a resolution of 600 dpi. The single leaf area was obtained by analyzed with DepositScan software, and average leaf area was calculated. The number of all the leaves in the 0.5 m height test area of the canopy was record. Assume that the test area was cylindrical, the leaves were evenly distributed in the canopy, and the leaf area density was calculated according to Equation (4).

$$L_{AD} = \frac{n\bar{s}}{\pi r^2 h} \tag{4}$$

where, L_{AD} is the leaf area density, m²/m³; n is the leaves number; $\bar{s}$ is the average leaf area, m²; r is the tree canopy radius, m; h is the test area canopy height, m.

3.3.2 Apple leaf maximum retention measurement

The maximum retention of apple leaf was measured by wetting method[29]. Dry apple leaf was weighed by the analytical balance. The leaf was clamped by tweezers and vertically submerged in clean water for 3-5 s. Then the leaf was pulled out of water and suspended vertically. The wet leaf was weighed when there were no more droplets dropped. Apple leaf area was obtained by scanning and analyzing with DepositScan software. The leaf maximum retention was calculated by Equation (5). The test was repeated 5 times for average value.

$$R_m = \frac{(W_1 - W_0)\times 1000}{s} \tag{5}$$

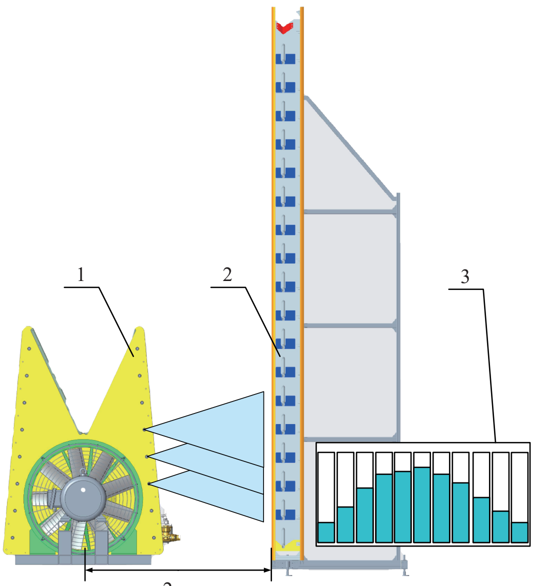
where, R_m is the maximum retention, μL/cm²; W_1 is the wet leaf mass, g; W_0 is the dry leaf mass, g; s is leaf area, cm².

3.3.3 Nozzle atomization characteristic measurement

Droplet size of each nozzle under pressure of 0.2-0.8 MPa was tested by DP-02 Laser Particle Sizer. The test result of droplet size was the average value of three repeated tests, and the spray quality was classified by droplet size[30]. The corresponding nozzle and spray pressure were selected to acquire fine spray quality.

3.3.4 Airflow speed and liquid distribution measurement

Wind speed of tower air-assisted spray test bench was measured by hot wire anemometer. According to the canopy diameter and leaf area density, the air outlet wind speed was selected from 10 to 15 m/s[7], correspondingly, the axial fan rotary speed was 1800 r/min. The static liquid distribution of tower air-assisted spray test bench was tested by lamellae vertical patternator[31]. The distance between lamellae vertical patternator and tower air-assisted spray test bench center was 2 m as shown in Figure 2. Spray time was 1 min, the test result was the average value of three repeated tests.



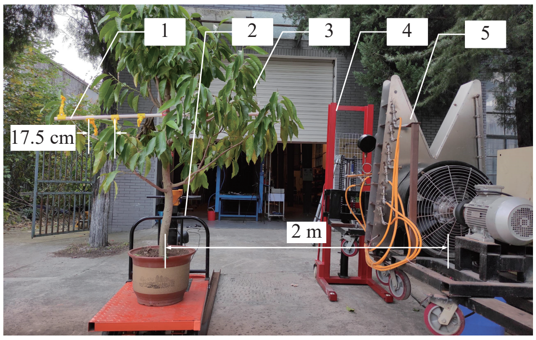
1. Tower air-assisted spray test bench 2. Lamellae vertical patternator 3. Liquid collector

Figure 2 Tower air-assisted spray test bench static liquid distribution measurement

According to tower air-assisted spray test bench static liquid distribution, the appropriate nozzle type, spray pressure and nozzle number were selected to meet the spray flow rate of different pesticide dose models.

3.3.5 Canopy deposition distribution measurement

The distance between tree trunk and the tower air-assisted spray test bench center was 2 m, as shown in Figure 3. The electric flat board vehicle was used to drag the tree to walk in a straight line, to simulate the walking motion of the spray machine, and the walking speed was 1 m/s. The double gantry manual stacker was applied to adjust the height of the tower air-assisted spray test bench, so that the liquid deposition area coincided with the test canopy area. A 1.4 m long sampling rod was horizontally fixed at the center of the test canopy area, and was perpendicular to the electric flat board vehicle forward direction. Nine universal clamps were evenly placed on the sampling rod[7], and the distance between universal clamps was 17.5 cm. The orientation of the universal clamps was staggered to reduce the interaction of deposition on water sensitive paper at each sampling point. The test was repeated three times.



1. Sampling rod 2. Electric flat board vehicle 3. White magnolia tree 4. Double gantry manual stacker 5. Tower air-assisted spray test bench

Figure 3 Canopy deposition distribution measurement

Water sensitive papers were collected and scanned into pictures with a resolution of 600 dpi after spray. The coverage density, coverage rate, and unit area deposition amount were obtained by DepositScan software analysis. Droplets were transported into the canopy by wind, the droplet penetration rate of different penetration distances was calculated by Equation (6).

$$P_j = \frac{F_j}{F_0}\times 100\% \tag{6}$$

where, P_j is the penetration rate of different penetration distances, %; F_0 is the coverage rate of outermost leaves near the sprayer, %; F_j is the coverage rate of different penetration distances, %; j presents different penetration distances of tree canopy, its values were set as 0, 17.5, 35.0, 52.5, 70.0, 87.5, 105.0, 122.5, 140.0 cm.

4 Results and discussion

4.1 Demand spray flow rate of pesticide application models

The tested potted white magnolia tree with a canopy diameter of 1.4 m, canopy height of test area was 0.5 m. Test results showed that, the average leaf area was 0.008 43 m²; the dense leaves number (before some leaves removed) n_1 was 422; and the sparse leaves number (after some leaves removed) n_2 was 203. According to Equation (4), the dense canopy leaf area density was 4.63 m²/m³, and the sparse canopy leaf area density was 2.23 m²/m³.

Take the plant mode of dwarf rootstock in modern apple orchard as an example, investigations in the field showed that the row spacing R was 3.5-4.5 m, conventional spray volume Q_{GA} was 1000-2000 L/hm². In this study, the row spacing R was set as 4 m, spray amount Q_{GA} was set as 1500 L/hm^2. Magnolia tree canopy parameters were substituted into Equations (1)-(3) to obtain spray flow rate of each pesticide dose model. Spray flow rate and spray parameters of each pesticide dose model are listed in Table 1.

Table 1 Spray flow rate and spray parameters of each pesticide dose model

Pesticide application model	Spray flow rate/L·min^{-1}	Nozzle type	Pressure/ MPa	VMD/ μm (Spary quality)	Nozzle number	Liquid deposition/ L·min^{-1}
LWA model	3.60	Solid conical spray nozzle 1.5 mm	0.4	174.74 (Fine)	3	3.73
TRV model	2.10	Solid conical spray nozzle 0.8 mm	0.6	163.80 (Fine)	3	2.06
OCM model with large leaf area density	0.81	Hollow conical spray nozzle 0.8 mm	0.3	163.69 (Fine)	3	0.86
OCM model with small leaf area density	0.39	Hollow conical spray nozzle 0.8 mm	0.3	163.69 (Fine)	2	0.44

It can be seen from Table 1 that the demand spray flow rate of the three pesticide dose models was gradually decreased. LWA model was only related to canopy height, TRV model was related to canopy height and canopy diameter, while OCM model was related to canopy height, canopy diameter and leaf area density. Therefore, the decrease of leaf area density has no effect on LWA model and TRV model. The selected nozzles spray qualities were fine. The liquid deposition volume of tower air-assisted spray test bench basically coincided with spray flow rate of each pesticide dose model.

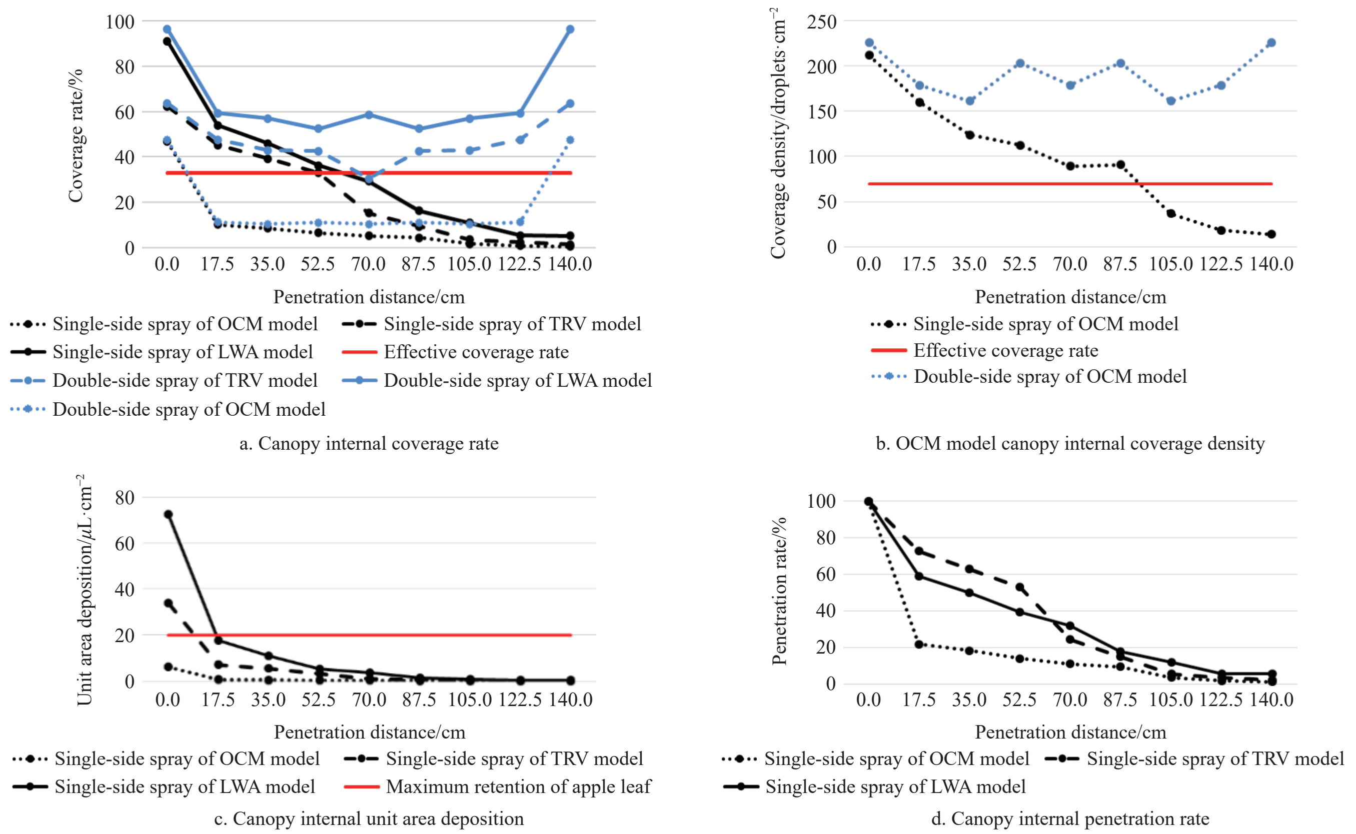
4.2 Droplet deposition distribution of canopy

Outdoor deposition experiments were conducted on November 4, 2021, in Nanjing, China. The average relative humidity, temperature and atmospheric wind speed was 63.1%, 20.5°C, 0.62 m/s, respectively.

According to apple leaf maximum retention measurement, the maximum retention of apple leaf was 20 μL/cm^2. According to the China Agricultural Standard[32], for conventional spray, the effective coverage rate should be greater than 33%; for low volume spray, the effective coverage density should be greater than 70 droplets/cm^2.

4.2.1 Droplet deposition distribution in dense canopy

Figure 4 shows the droplet deposition characteristics in the canopy with L_{AD} of 4.63 m^2/m^3. According to the deposition data of single-sided spraying, the values of left and right sides were added symmetrically to draw double-sided spraying deposition diagram. As can be seen from Figure 4a, under double-side spray conditions, LWA model and TRV model basically met the requirement of effective coverage rate greater than 33% in the whole canopy, however, OCM model coverage rate in entire canopy was less than 33%. As can be seen from Figure 4b that OCM model met the requirement that the effective coverage density was greater than 70 droplets/cm^2. Figure 4c shows that LWA model unit area deposition of outermost leaves near sprayer was 72.39 μL/cm^2, which was 3.6 times of the apple leaf maximum retention and indicated a high loss risk. Figure 4d shows that the penetration rates decreased sharply with the increase of penetration distance in dense canopy.



a. Canopy internal coverage rate

b. OCM model canopy internal coverage density

c. Canopy internal unit area deposition

d. Canopy internal penetration rate

Figure 4 Droplet deposition characteristics in the canopy with L_{AD} of 4.63 m^2/m^3

4.2.2 Droplet deposition distribution in sparse canopy

Figure 5 shows the droplet deposition characteristics in the canopy with L_{AD} of 2.23 m^2/m^3. As can be seen from Figure 5a, under double-side spray conditions, LWA model and TRV model had uniform coverage rate in the whole canopy, and met the requirement of effective coverage rate greater than 33% in entire canopy, while the OCM model coverage rate was less than 33%. As can be seen from Figure 5b, OCM model meets the requirement that the effective coverage density greater than 70 droplets/cm^2. Figure 5c shows that the deposition of LWA model and TRV model in the canopy was similar, there was a certain loss risk between 0-35 cm deposition distance. Figure 5d shows that the penetrationrates stabilized with the increase of distance at first, and then decreased sharply when the penetration distance reached 35 cm. The outermost leaves far away sprayer penetration rates of LWA model and TRV model were 21.4% and 10.3%, respectively, indicated that drift rate of LWA model was 21.4%, which was twice of TRV model.

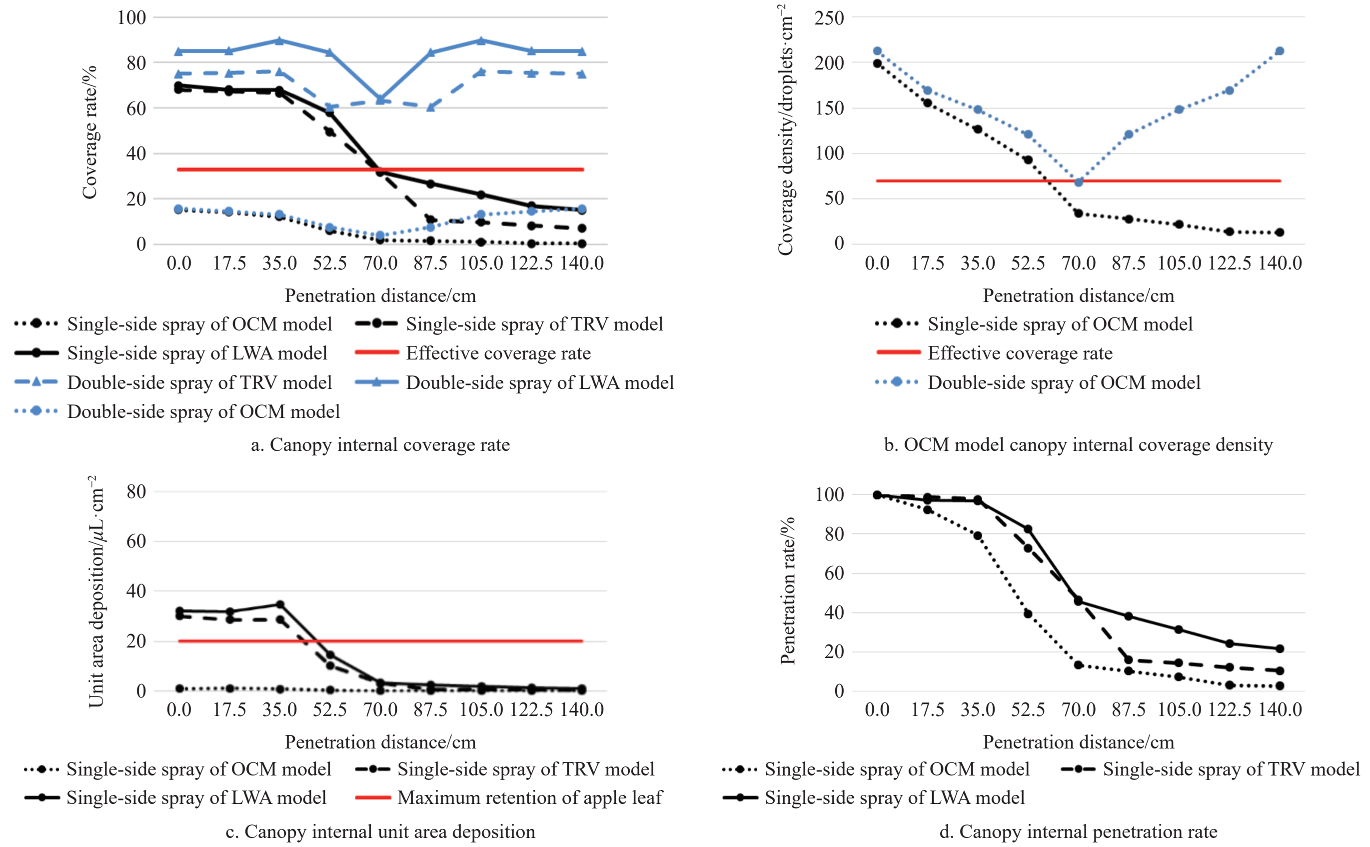


Figure 5 Droplet deposition characteristics in the canopy with L_{AD} of 2.23 m^2/m^3

5 Conclusions

Orchard pesticide dose models are the basis for the spray amount adjustment according to the fruit tree canopy parameters. In this article the spray flow rate calculation methods of LWA model, TRV model and OCM model were summarized. LWA model was only related to canopy height, the variable of TRV model was canopy volume, while OCM model included not only canopy volume but also leaf area density. The spray flow rates of the three models were decreased gradually. Results of droplet deposition distribution in the canopy with different leaf area density showed that, whether dense or sparse canopy, LWA model and TRV model basically met the requirement of coverage greater than 33% in the entire canopy, OCM model met the requirement of coverage density greater than 70 droplets/cm^2. However, LWA model had a high loss risk for dense canopy, and had a high drift risk for sparse canopy. The discussion leads to the conclusion that, TRV model was a reasonable conventional spraying model, and OCM model was a reasonable low volume spraying model.

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