Current Research on Deposition and Drift of Droplets Sprayed by Plant Protection UAV

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Article

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Abstract

Plant protection UAV, which is highly adapted to terrain and capable of efficient low-altitude spraying, will be extensively used in agricultural production. This paper systematically sorts out the single or several independent factors influencing the deposition characteristics of droplets sprayed by plant protection UAV, as well as the experimental methods and related mathematical analysis models used to study the droplet deposition and drift. It proposes a research method based on farmland environmental factors to simulate the deposition and drift characteristics of pesticide droplets, further studies the impact of multiple factors on the droplet deposition characteristics by using an indoor simulation test system for the spraying flow field of plant protection UAV to simulate the plant protection UAV spraying flow field, temperature, humidity and natural wind and integrating the operation parameters, environmental conditions, crop canopy characteristics and rotor airflow, explores the main effects and interactive effects of the factors influencing the deposition of pesticide droplets, establishes a mathematical model which can reflect the internal relations of multiple factors and evaluate and analyze the droplet deposition characteristics, and further proposes a scientific and effective method for determining the optimal pesticide droplet deposition. In addition, it also proves that this research method can provide a necessary scientific basis for the formulation of operating standards for plant protection UAV in China, inspection and evaluation of operating tools at the same scale, and the improvement and upgrading of spraying systems.

1. Introduction

In agriculture, aerial spray is widely used to spray fertilizers, herbicides, fungicides and other materials used for crop protection[1]. Compared with large fixed-wing agricultural aircraft, small UAV is particularly advantageous because it is highly maneuverable without any airport for taking off or landing[2]. In recent years, aerial machinery for plant protection, especially aerial spray by small plant protection unmanned aerial vehicles (UAV), has developed rapidly in China[3]. In southern China, with paddy fields and hills as the main areas, small plant protection UAV has greater application prospects in agricultural production because of its better terrain adaptability and low-altitude spraying capability (Fig.1 - 3)[4-7]. However, UAV spraying technology is an emerging technology which involves problems such as poor droplet deposition distribution uniformity and low drop deposition level in the control of agricultural diseases and pests as a result of lack of operating standards and uncertain optimal spraying parameters.

Overseas studies have shown that if the aerial spraying parameters are not set scientifically, it will lead to not only repeated spraying and missed spraying, degrading the effect of pest control, but also cause pesticide drift[8]. The use of new pesticide additives and the innovative research and development of precise spraying equipment of plant protection UAV along with its safe and efficient use in the prevention and control of diseases, pests and weeds are indispensable means to increase the pesticide deposition amount and reduce drift. Studying the deposition characteristics of pesticide droplets is not only of scientific significance for the development of new pesticide formulations and precise spraying equipment of plant protection UAV, but also of practical guiding significance for the safe and efficient use of pesticides in the farmland. Impacted by many factors such as natural environment, pesticide characteristics, crop canopy characteristics, and plant protection UAV operating parameters, it is a complicated process to study the uniformity and penetration of pesticide droplets. In order to improve the spraying effect and reduce drift, scientific and technological workers all over the world have carried out a large number of exploratory studies on the deposition and drift characteristics of pesticide droplets through field or wind tunnel experiments or mathematical model analysis[9-13], main factors and secondary factors influencing the characteristics of droplet deposition and drift are sorted out from the many influencing factors (nozzle, droplet, aircraft type, weather factors, etc.), and the functional relationship between the amount of different droplet deposition and drift and their influencing factors are determined. However, there are not sufficient deposition models for plant protection rotor UAV, and the existing models consider only a few influencing factors, which need to be further modified. With the development of UAV technology, there are more and more researches on the droplet deposition rules, operation parameter optimization and evaluation methods of pesticide applied by plant protection UAV in rice fields and maize fields, etc[14-17], but these studies have defects that the meteorological factors in the farmland environment are unstable and uncontrollable, the UAV track is easy to deviate, resulting in poor uniformity of droplet deposition distribution (the coefficient of variation may be above 40%[16], while it is usually below 10% for spraying by ground equipment), the test result cannot be well repeated, and different types of UAV cannot be easily evaluated at the same scale, so it is difficult to evaluate the droplet deposition characteristics of different types of UAV scientifically. Some research has established mathematical models to study the impact of plant protection UAV operating parameters (operating height, operating speed, and spraying flow rate) on droplet deposition and drift characteristics[18-20], and found out the main effects influencing droplet deposition, but due to the lack of conformity between the assumptions of these models and the farmland practice, they neglected the influence of characteristics of the crop canopy and the interaction of multiple factors such as the environment, crops, and operating parameters of application equipment on the droplet deposition characteristics (uniformity of distribution and penetration), making the results obtained through analysis with existing mathematical models highly deviate from the practice.

2. Research On Influencing Factors Of Pesticide Droplet Deposition Characteristics

To study the droplet deposition characteristics (uniformity and penetration) is always a major subject in pesticide application technology research. Relevant Chinese and foreign research results show that the deposition characteristics of pesticide droplets are influenced by the application technology and equipment, crops, and environment, mainly including meteorological conditions, wind speed, wind direction, leaf area index, target crop canopy structure, leaf inclination angle, leaf surface characteristics, droplet group characteristics (release height, release rate, pesticide droplet amount and droplet size spectrum), etc[21-24]. Diepenbrock pointed out that plant leaf size, leaf inclination angle, drooping degree and spatial arrangement and other characteristics have an impact on the composition quantity and distribution quality in the crop canopy structure, further impacting the penetration and deposition of droplets[25]. Song et al found through study that changing the initial velocity of the droplets will increase the deposition amount on the horizontal and vertical targets[26]. In the spraying of plant protection UAV, the influencing degree of factors such as flying altitude and flying speed of different types of aircraft on the deposition and drift of droplets is mostly studied. Qiu et al studied the deposition distribution rules of droplets sprayed by unmanned helicopters at different flying heights and speeds under field conditions by an orthogonal experimental method, and established a relationship model to study the interaction between deposition concentration, deposition uniformity and flying speed, and flying height, as well as between flying speed and flying height, and this model can be used as a reference for the optimization of spray operation parameters[19]. Chen et al studied the deposition distribution rules of droplets sprayed on the rice canopy by single-rotor electric UAV in the field environment, and the result showed that the flying height and flying speed have a significant effect on the average deposition of droplets on the collection points in the target area, but no significant effect on the uniformity of droplet deposition[27]. Wang et al studied the deposition distribution ratios of droplets sprayed by single-rotor oil-powered UAV and multi-rotor electric UAV in different directions at the same operating height and operating speed in a field environment, proving that the downward swirling airflow under UAV is an important factor impacting the droplet deposition distribution[14]. Wang et al. studied the influence of variables such as the PWM duty cycle of aerial nozzles, spout aperture diameter, and electric centrifugal nozzle rotating speed on the droplet deposition rule with the controllable multi-wind speed environment of a wind tunnel, and pointed out that wind speed is the most significant factor influencing the droplet deposition effect, followed by the droplet size[15]. Qin et al studied the influence of unmanned helicopter application on the droplet deposition distribution on the rice canopy in a field environment, showing that the main factor influencing the droplet deposition amount is the flying speed, and the main factor influencing the uniformity of the droplet deposition distribution is the flying height[20].

In summary, there are many factors influencing the deposition characteristics (uniformity and penetration) of pesticide droplets. However, most of the current researches on spraying by plant protection UAV, only the influence of such factors as flying height and flying speed on the droplet deposition in the field environment is taken into consideration. Considering the influence of interaction between environmental factors, crop canopy characteristics (growth stage, leaf area index, leaf inclination angle) and plant protection UAV spraying parameters on the droplet deposition characteristics, there is neither in-depth understanding nor relevant report especially under controllable environmental conditions (Fig.4). To promote the high-efficiency spraying technology for plant protection UAV, targeted basic researches should be carried out on the analysis of the influencing factors of plant protection UAV spraying and the optimal deposition of droplets.

3. Research On Experimental Means And Testing Methods Of Droplet Deposition And Drift

At present, the deposition and drift of droplets are mainly researched by field test and wind tunnel test[28-31]. Field test research of pesticide deposition and drift is closer to the actual situation, but it is quite difficult to acquire correct data due to the constant changes of meteorological factors such as wind speed, wind direction, temperature and humidity. In addition, Emilia et al pointed out that the terrain and plant morphology also influence the wind flo11w and droplet deposition, leading to considerable deviation among repeated test results[32]. Therefore, it is difficult to accurately determine the total amount and distribution of pesticide drifting in the air. The wind tunnel laboratory can provide a controllable environment to simulate the external spraying conditions, which can easily control the wind speed and direction, and therefore, it is an important means to study the drift characteristics of spraying components and avoid many defects in field test research[10,33]. The typical wind tunnels which are widely used in agricultural aviation spraying technology at domestic and overseas are shown in table 1[34].

Table 1: Typical wind tunnel used for agricultural aviation spray at home and abroad

No	Name	Speed / (m · s^{-1})	The test section size / m (width × height × length)	Architectural feature	Main application	Institution
1	Silsoe	0-15	4 × 2 × 5	Eiffel type	Spray drift and nozzle structure features	SRI
2	LSWT	0.2-6.7	1.2 × 1.2 × 14.6	Direct current closed	Spray drift, droplets bead spectrum and nozzle structure; DRT technology	USDA- ARS
3	HSWT	Up to 90	0.3 × 0.3 (open type, without fixed aspect ratio)	Direct current closed	Spray drift, droplets bead spectrum and nozzle structure; DRT technology	
4	ATB	0-20	3 × 2 × 20	Boundary layer wind tunnel with rotating platform	Complex landform droplets drift, poultry breeding cycle ventilation facilities	Germany's leibniz institute of agricultural engineering
5	-	0-5	2 × 2 × 6	Turbulence wind tunnel	Freon, spray drift, Droplets bead spectrum	Belgium Gembloux AgroBioTech Agricultural University
6	-	Up to 83	1.75 × 1 × 10	Air conditioning open circuit closed	Spray drift, Droplets bead spectrum, Nozzle classification	CPAS
7	JKI(BBA)	0.3-15	2.5 × 1.6 × 10	Air conditioning backflow closed	Members of the European Union for performance test of spraying parts and machinery anti floating contrast grading	JKI BBA
8	NJS-1	1.0-10	1.2 × 1.8 × 7.5	Direct current closed	The performance testing of spray plant protection machinery	Nanjing Agricultural Mechanization Institution

Internationally well-known professional research institutions for pesticide application, such as the Julius Kuehn Institute-Federal Research Centre for Cultivated Plants (JKI, formerly BBA) and USDA-Agricultural Research Service, Application Technology Research Unit (USDA-ARS-ATRU), have a circular closed low-speed standard wind tunnel (Fig.5), and the Silsoe Research Institute, UK (SRI) has a standard linear low-speed wind tunnel, and the Center for Pesticide Application and Safety (CPAS) of the University of Queensland in Australia has an open-path wind tunnel (Fig.6). In 2014, Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs built the NJS-1 plant protection direct flow closed wind tunnel (Fig.7); in 2018, the National Center for International Collaboration Research on Precision Agricultural Aviation Pesticides Spraying Technology of South China Agricultural University built a high and low speed composite wind tunnel for agricultural aviation research (Fig.8). As the basic conditions for technical research, these wind tunnels have made great contributions to the study of pesticide deposition and drift rules, product testing, and product optimization[35-38]. However, for the study of pesticide droplet deposition and drift under the disturbance of the wind field of plant protection UAV, the single-direction wind tunnel simulation test is still insufficient to simulate the combined effect of the downward swirl flow under the rotor and the natural wind. In addition, the existing agricultural wind tunnels are limited in size, so plant protection UAV cannot be put in. In military, a scaled model method is taken to put UAV into wind tunnels for research[37], but it is not suitable for the research of pesticide spraying with plant protection UAV, and the airflow will rebound from the tunnel wall.

Another important test technique for drift research is the sampling and analyzing of droplet drift. Test researches on the drift of aerial mist in developed countries such as the United States and Germany are carried out with advanced test instruments including automatic air sampler, gas or liquid chromatography, fluorescence analyzer, and electronic scanners, etc. to collect and analyze the droplet deposition amount, the number of droplets, the coverage density of droplets, and the content of substances, and study the correlation between additive concentration, spraying height and drift[39,40,4]. However, these traditional methods involve a long collecting and processing cycle, samples have to be processed in lab, and it is difficult to express the dynamics droplets in air. Particle Image Velocimetry (PIV) and LIDAR scanning test method can solve the above problems, and each has its own advantages. PIV can obtain the three-dimensional spatial velocity vector of droplets and droplet size with high sampling accuracy but limited spatial measurement scale[41,42]; the LIDAR scanning method, realized by layered scanning, can quickly and accurately obtain the large-scale spatial droplet point cloud data, inversely form the three-dimensional distribution and temporal-spatial change of the droplets, but cannot reflect the spatial velocity vector change of the droplets[43,44]. The advantages, disadvantages and applications of droplet deposition and drift measurement methods are shown in Table 2[45].

Table 2: Advantages, disadvantages and applications of various measurement methods

Measurement method	Acquirable information	Advantage	Disadvantage	Application
Spot method	Droplet size	The principle is simple, and the original form of the droplets can be preserved	The operation is complicated and limited by the testing site	Indoor testing
Paper card method	Droplet size and coverage	Simple operation and intuitive result	The measurement accuracy is impacted by the diffusion coefficient of the test paper	To acquire the droplet size and coverage of representative areas
Cotton thread or nylon thread method	Droplet deposition amount	Tiny droplets can be captured	Data processing is complicated	Droplet drift
Stain method	Droplet deposition amount, droplet size and distribution	Low cost	Data processing is complicated, and the result accuracy is not high	Where accuracy is not much required
Fluorescent particle tracing method	Droplet deposition amount	High cost and high accuracy	Droplet size and distribution cannot be acquired	Outdoor detection focusing on acquiring the deposition amount
Phase Doppler particle analysis	Droplet velocity, particle size, spray angle, number of droplets per unit time	High measurement accuracy	Not suitable for the detection of large droplets	Droplet field with smaller droplet size
Laser/droplet image analyzer	Droplet size and moving speed	Real-time images of the droplet field can be acquired, high measurement accuracy	Not suitable for detection of droplet field with a high droplet density	Droplet field with low droplet density
Laser particle size analyzer	Cumulative distribution ratio of any droplet size to an interval between Dv0 and Dv100	High measurement accuracy	Only the droplet data on the laser line can be acquired	An indoor test to acquire the droplet size distribution

4. Research On Mathematical Analysis Model Of Pesticide Droplet Deposition Characteristics

In the development of spraying equipment and the determination of the optimal deposition conditions for spray, a large amount of data and information are needed to explain the influence of different factors on the spraying performance and the relationship between variables. At present, spraying drift modeling at home and abroad can be divided into models based on mechanics and models based on statistics. One of the models based on mechanics analyzes the movement of a single droplet in the airflow field by the Lagrangian trajectory tracking analysis method. Teske et al established the AGDISP model by the analytical Lagrangian method to describe aerial spraying under the condition of ignoring the influence of aircraft wake and atmospheric turbulence[41]. This model takes not only the aircraft type, environmental conditions, and droplet properties, but also the influence factors of the nozzle model into consideration. The user can input the parameters of nozzle, droplet, aircraft type and weather factors, etc. from an internal database and predict the possible drift. It can effectively and accurately predict a range of 20 km, but is mostly used for fixed-wing aircraft. Duga et al and Gregorio et al studied the deposition distribution of air spray in orchards also with the Lagrangian discrete phase model, and the result of the numerical model showed that the prediction error of total deposition on fruit tree canopy is above 30%[43,46]. Another model based on mechanics is realized with the CFD (Computational Fluid Dynamics) method[47], but there are still large errors between the simulated value and the real value of some models due to various factors. Holterman et al carried out a series of cross-wind single nozzle field experiments in consideration of traveling speed, entrained airflow, geometric parameters of the farmland, sprayer system setting parameters and environmental factors when studying the droplet deposition drift model of ground boom sprayers to calibrate the mathematical model, the result showed that when the height from the crop canopy is less than or equal to 0.7 m, the error between the test and the model simulation is within 10%, but the error between droplet deposition and drift prediction gradually increases as the height of the spray boom increases[48].

Chinese scientific and technological workers have conducted some experimental research and numerical analysis on the numerical simulation and mathematical modeling of spraying droplet deposition and drift prediction of ground plant protection equipment, and drawn some conclusions that physical quantities such as operating speed, droplet size and crosswind impact the droplet deposition and drift process (Fig.9 - 10). Qi et al established an orchard air blower sprayer droplet deposition distribution model based on CFD technology[49]. The simulation result of the model showed that the average relative error increased from 33.35% to 146.85% at the position of 140cm-340cm from the center of the fan, where the droplet deposition characteristics cannot be accurately simulated. Zhang et al modeled the deposition and drift distribution of droplets sprayed by an ultra-high ground clearance boom sprayer with a simulation software, and performed corresponding experimental studies[50]. The result showed the correlated error between the simulation value and the experimental value is between 31% and 48% with the increase of fan speed. Moreover, in terms of agricultural aerial spraying deposition and drift, Zhang et al simulated the two-phase flow of the rotor wind field and pesticide spraying under constrained conditions by a computational fluid dynamics method, and the result showed that at the same flying height when the crosswind is 2m/s and the distance from the spraying area is 2m-20m, the relative error between the experimental value and the simulation value increases from 138.7% to 2400%, which is too large[18].

The above research proves that computer simulation technologies are widely applicable to the prediction research of droplet deposition under various complicated wind-supply airflow conditions. The existing AGDISP model abroad is relatively mature, and only suitable for the research of fixed-wing aircraft, which is highly different from the research of plant protection UAV. The domestic plant protection UAV spraying prediction model still has problems such as large relative errors between the experimental value and simulation value of the deposition and drift at each measurement point. Therefore, the prediction accuracy of the numerical model for the spray droplet deposition of plant protection UAV is still low and needs to be improved, and there is a lack of in-depth basic researches on analyzing the rotor flow field and establishing mathematical analysis models for droplet deposition.

Conclusion

Existing researches on plant protection UAV spraying are mainly limited within the influence of a single factor or several independent factors such as flying height, flying speed and nozzle flow, etc. on the droplet deposition characteristics without consideration of the interaction effects among other influencing factors such as operating parameters, environmental conditions and crop canopy characteristics. Therefore, in order to scientifically evaluate the spray droplet deposition characteristics of plant protection UAV influenced by multiple factors, it is also necessary to carry out experimental researches on the pesticide droplet deposition characteristics (uniformity and penetrability) in combination with crop canopy characteristics in an environment where environmental conditions and operating parameters are controllable. Factors influencing the deposition characteristics of pesticide droplets can be statistically analyzed to quantify the experimental parameters and establish a multi-variable relationship model of optimal droplet deposition suitable for the field operation decision making of plant protection UAV. It can provide an effective technical path for evaluating the farmland deposition rule of droplets sprayed by plant protection UAV, and theoretically support the formulation of relevant pesticide application standards for plant protection UAV. Therefore, this paper proposes an indoor simulation test system for the spraying flow field of plant protection UAV to track the dynamics of local droplet flow field in the air in combination with a natural wind simulation system by the fluorescence tracer method and high-speed camera method, which provides a new train of thought for the research on the droplet deposition characteristics and an effective and scientific method for analyzing the droplet deposition characteristics influenced by multiple factors (Fig.11). The method is subject to further study in the future.

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Figures

Figure 1

Fixed-wing aircraft spraying

Figure 2

Single-rotor UAV spraying

Figure 3

Multi-rotor UAV spraying

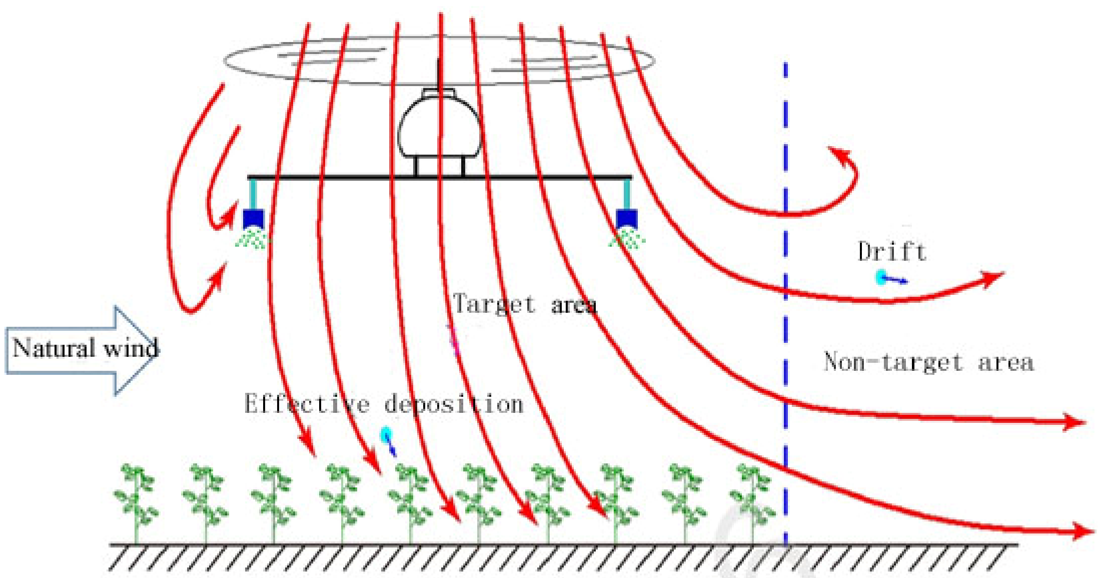

Figure 4

Description of deposition and drift with Rotor UAV spraying

Figure 5

Circle closed low speed wind tunnel

Figure 6

Open wind tunnel

Figure 7

NJS-1DC closed wind tunnel

Figure 8

High and close speed composite wind

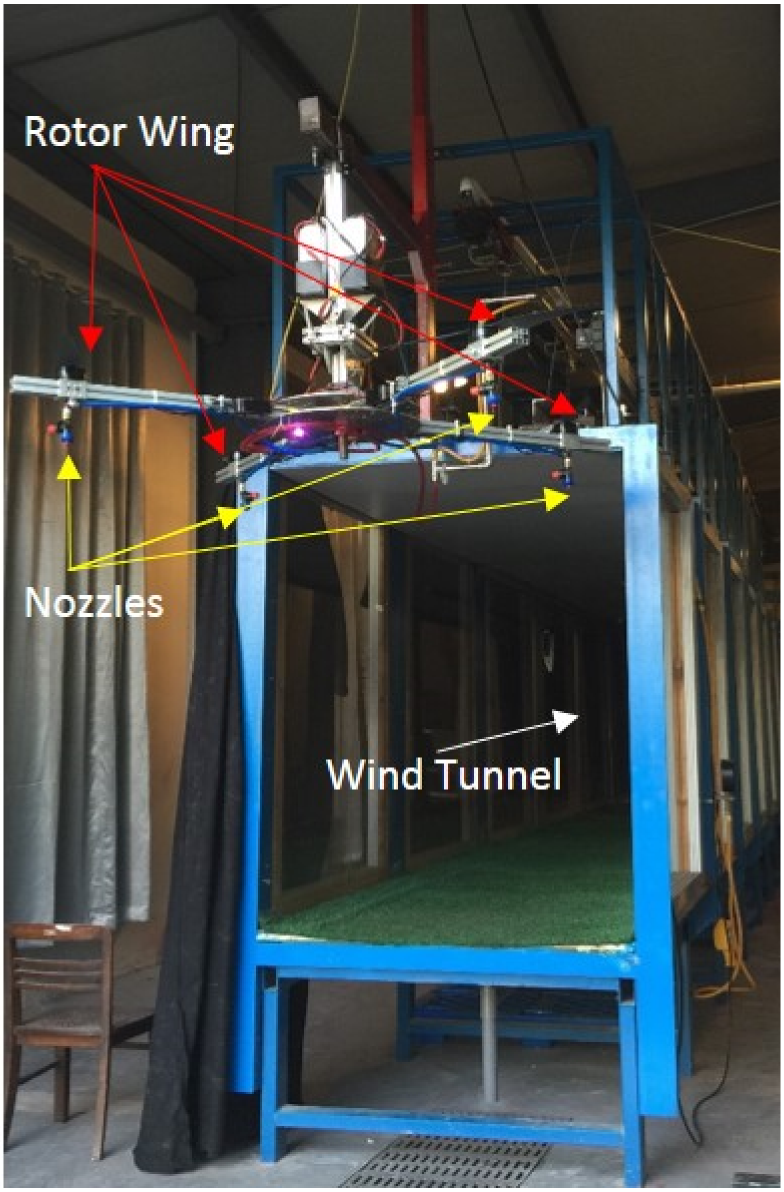

Figure 9

Rotor wind field test platform based on wind tunnel

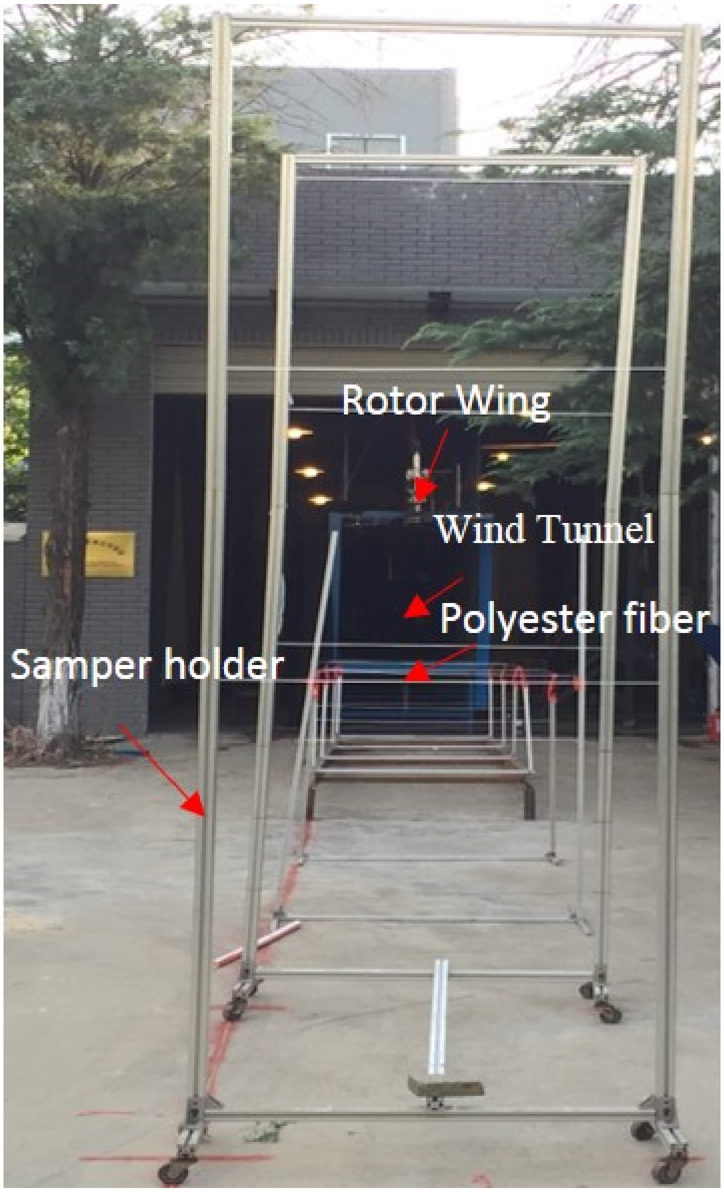

Figure 10

Layout scene of droplets drift

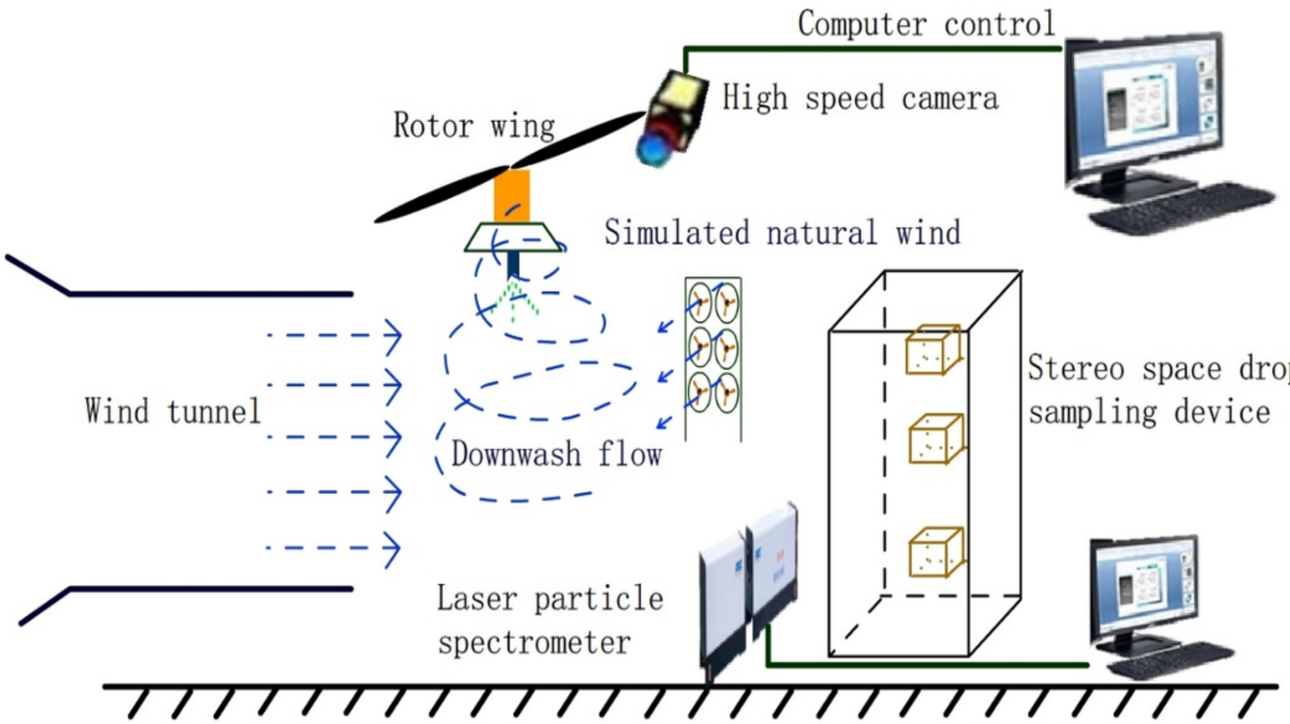

Figure 11

Diagram of rotor wind field test platform and droplets drift