Key technologies for testing and analyzing aerial spray deposition and drift: A comprehensive review

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Abstract: The technologies for testing and analyzing aerial spray deposition and drift serve as the tools and foundational technologies for spray deposition and drift modeling, deposition and drift control, and the development of aerial spray equipment. These technologies can be categorized into four types by comprehensively considering their testing analysis methods, analysis objects, and application technologies: sampling, laboratory simulation, computer simulation modeling, and new analysis technologies. With regard to sampling analysis technologies, this study mainly analyzed the water-sensitive paper (WSP) sampling testing method, tracer testing method, combined WSP and tracer testing method, as well as the electronic information technologies that have been widely used and rapidly developed in recent years. With respect to the laboratory simulation analysis technologies, this paper elaborates on the applications of laser particle size measurement technology and instrument based on the laser diffraction principle, particle image velocimetry technology and instrument, phase doppler interferometer based on laser scattering principle, and other spray measurement technologies. In case of computational modeling simulation analysis technologies, this paper mainly expounds the spray deposition model analysis and research methods based on the Gaussian plume, Lagrange, statistical, and computational fluid dynamics (CFD) models. Additionally, the paper describes the applications of LIDAR, thermal infrared imaging, and other technologies to the analysis of spray deposition. Electronic technology, computer technology, and other information technologies are being used more widely for analyzing aerial spray deposition, and have become a development trend in recent years. The instruments rapid measurement of spray deposition in the field and the real-time accurate prediction models for spray drift are in high demand. The instrument for rapid in-field measurement should be compact, exhibit good portability and convenience of use in the field, and guarantee high measurement accuracy. The spray deposition and drift mechanisms are relatively well clarified, and the use of advanced technologies to develop practical instrument is the main work of future research in this area.

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1 Introduction

Aerial pesticide application uses low-volume or ultra-low-volume spray technologies. These can effectively reduce the amount of pesticide and solve the problem of difficult access for ground machinery to the woodland, hills, and fields. Moreover, these technologies are in line with the global development trend of modern agriculture and China’s strategy of “accelerating the development of agricultural mechanization”[1-2]. In recent years, aerial pesticide application technologies have been developed rapidly and are becoming the backbone of agricultural pest control. In particular, unmanned aerial vehicles (UAVs) for plant protection, which has been actively promoted by the Chinese government, have achieved substantial development. According to incomplete statistics, the number of plant protection UAVs owned by China had reached 695 units and the operation control area had reached 4.26 million mu times in 2014. In 2019, the number of plant protection UAVs owned by China had reached 54,600 units and the operation control area had nearly reached 500 million mu times[3]. Application scope will increase rapidly in the next 1-3 years. They have tremendously transformed the chemical plant protection and mechanization operation.

When an aerial operation approach is adopted, the motions of spray droplets are severely affected by the rotor airflow and environmental factors. Furthermore, the environmental pollution caused by pesticide drift is becoming the focus of aerial pesticide application technology[4-5]. The quantitative analysis and measurement of aerial spray deposition and drift using various technical methods are a current research hotspot, and thus, a variety of testing and analysis technologies have emerged. These technologies can be categorized into four types by comprehensively considering their testing analysis methods, analysis objects, and application technologies: sampling,

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laboratory simulation, computational modeling simulation, and new analysis technologies.

This paper systematically elaborates on the research status of the key testing and analysis technologies for aerial spray deposition and drift, analyzes the problems in the current testing technologies and prospects and considers the future development of advanced testing technologies.

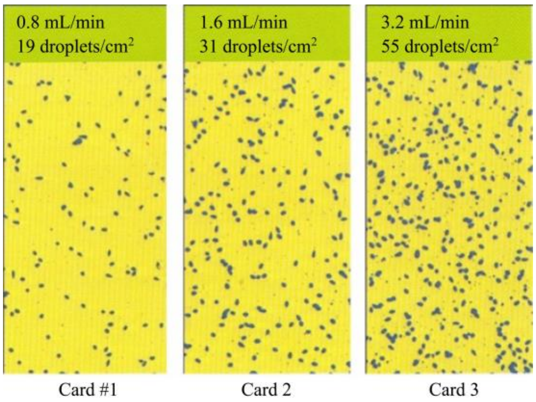
2 Sampling analysis technology

Field tests have high practical significance in the research on the droplet deposition effect and atomization status of aerial pesticide spray. The acquisition of spray droplet deposition parameters serves an important part in improving the spraying effect. Early traditional methods for measuring spray deposition include magnesium oxide plate, oil-coated, and filter paper calibration methods[6-7]. However, severe evaporation and condensation of small droplets occur in places with high temperatures and dryness. This hinders the retention of samples for observation. In addition, the preparation of magnesium oxide plates is complicated, expensive, and has relatively low accuracy. The oil-coated method can better maintain the shapes of droplets, prevent small droplets from evaporating and shrinking, and provide more accurate readings. However, both the oil-coated and filter paper calibration methods require a microscope to measure the droplet stain diameter. When the number of droplets is large, the corresponding workload would also be large. This increases the tendency of the methods to produce repeated and missed readings. Currently, the water-sensitive paper (WSP) sampling and analysis technology based on computer image recognition as well as the tracer analysis and measurement method are the mainstream applications. In addition, the application of electronic sensor technology is gradually becoming wider.

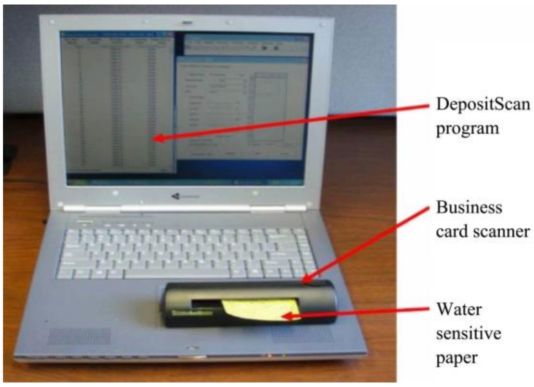
2.1 WSP sampling analysis technology based on computer image recognition

WSP is a method that was adopted relatively early for obtaining droplet deposition. Because of its apparent color development and convenient image processing after scanning, it is still widely used for measuring the pesticide droplet distribution after field application tests. In 2011, Zhu et al.[8] developed a portable scanning system to rapidly evaluate the deposition distribution and coverage areas of droplet collectors such as WSPs and Kromekote cards, under different conditions. The DepositScan software can calculate parameters such as the droplet size and their distributions, total number of droplets, coverage, deposition density, and deposition amount. The system can rapidly evaluate the spray deposition distribution on WSPs or Kromekote cards, thereby providing a convenient approach for the on-site evaluation of aerial spray. Moreover, DepositScan has evolved into a mature, mainstream, and widely used software for evaluating droplet deposition effects. The scanning system are shown in Figure 1.

Some scholars have studied the adhesion and coverage of spray droplets on WSPs to improve the accuracy of spray droplet image recognition. Xu et al.[9] proposed a method for separating overlapping droplet images by erosion and calculating the droplet diameters using the image grayscale depth. Furthermore, they developed iDAS, an image processing system (Figure 2) for evaluating spray droplet deposition which has better system performance for analyzing the WSP image with high-coverage compared with the DepositScan system. However, the two systems have similar performances in terms of analyzing the WSP images with medium and low coverage.



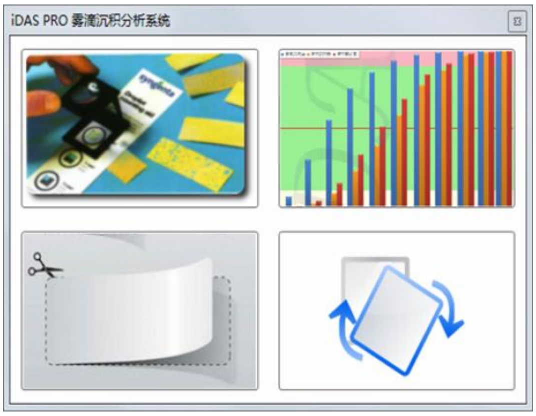
a. Droplet result of Syngenta water sensitive papers



b. The scanning system consisting of a business card scanner, a computer, and the DepositScan program

Figure 1 The portable spray deposition scanning system

a. Portable scanner



b. iDAS Pro software

Figure 2 Image processing system for aerial application quality evaluation

A few spray droplet analysis devices and applications used in conjunction with smart mobile devices have been developed and applied in recent years to achieve rapid measurement of spray droplet deposition in the field. Nansen et al.[11] developed a new smartphone application, SnapCard (Figure 3). Ferguson et al.[10] compared this application with five other imaging systems in the market for the quantitative analysis of the droplet deposition amount on WSPs and Kromekote cards, and their results demonstrated that the SnapCard application has certain practicality.

a. SnapCard application in sprayed fields

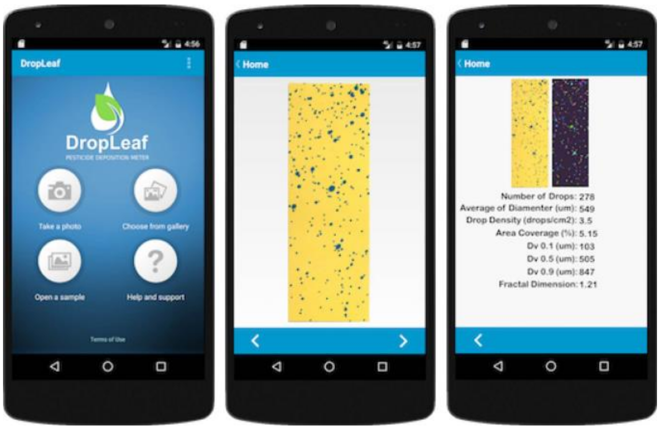
50.1% estimated coverage

Note: Ensure a sharp image or droplet coverage will be under estimated.

b. The screen of SnapCard.

Figure 3 Ground rig spray application

Machado et al.[12] proposed a new method based on a smartphone application, DropLeaf (Figure 4), and experimentally evaluated the method. The WSP images were captured in the field in real time, the spray coverage was calculated immediately, and the extent of pesticide spray coverage in the target crop area could be predicted rapidly and accurately.



Number of Drops: 278
Average of Diamenter (um): 549
Drop Density (drops/cm2): 3.5
Area Coverage (%): 5.15
Dv 0.1 (um): 103
Dv 0.5 (um): 505
Dv 0.9 (um): 847
Fractal Dimension: 1.21

Figure 4 A preview of fully functional DropLeaf application

2.2 Tracer-based analysis technology

The image processing method based on WSP is cumbersome, labor-intensive, and yields results with relatively low accuracy owing to the long recovery time. In addition, the accuracy of the image processing results is closely related to the coverage. Derksen et al.[13] and Cunha et al.[14] from the U.S. Department of Agriculture (USDA) have observed in their research that when the coverage is high, there is a large error between the image processing result and actual deposition owing to the influences of spray droplet coverage and adhesion. Whereas methods based on WSPs can effectively measure droplet size, deposition coverage density, and other related parameters, it cannot accurately obtain the amount of droplet deposition. Therefore, many studies added fluorescent tracers to the spray liquid before application. The spray droplets are then collected with a glass slide, polyester card, photo paper, etc., and the fluorescence of the tracer eluent is measured using a fluorometer. Finally, the deposition amount of spray droplet is calculated using corresponding equations. Sharp et al.[15] added different types of fluorescent dyes (water-soluble dyes, oil-soluble dyes, and pigments) to the spray liquid as fluorescent tracers. They discussed the emission spectra of fluorescent dyes, calibration, the effect of pH variations, and fluorescence stability. In addition, they provided a sensitive method for measuring spray depositions on leaf, soil, wood, and paper substrates. Bradley et al.[16] compared the fluorescence of processed samples with that of reference samples with known dye concentrations for measuring the aerial spray drift and deposition on crops. This provided a reference for other researchers to adopt this method. Torrent et al.[17] collected brilliant sulfaflavine tracers with nylon threads and measured the tracer concentrations with a fluorometer after elution. The measurements were then used to determine the amount of spray deposition. Brian et al.[18] collected the spray droplets of a fluorescent tracer solution with white poly-cotton blend ropes and steel plates simultaneously. They measured the fluorescence intensity on the rope using a fluorimeter, light-emitting diode (LED), and bandpass filter. The concentration of the fluorescent tracer solution was measured using the Jenway 6285 fluorimeter, and the deposition amount of the spray liquid was calculated. Recently, the development of tracer analysis technology has mainly focused on the exploration and application of various new tracers, development of tracer solution analysis instruments, and research on the influence of different pesticides on the testing accuracy of tracer concentrations in solutions.

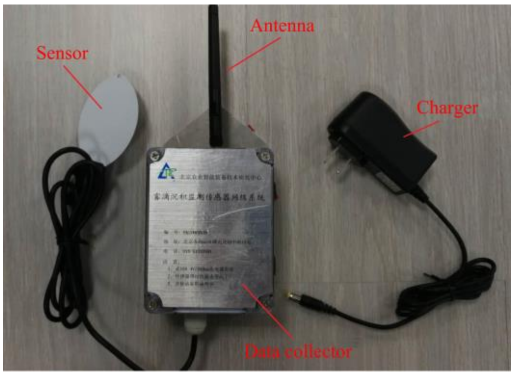
2.3 Analysis technology combining WSP and tracer

In many studies, two measurement methods, namely, WSP and fluorescent tracer, are combined to test and analyze the quality of aerial pesticide application more comprehensively and accurately. Huang et al.[19] collected the droplets of the mixed solution of glyphosate and rubidium chloride tracer using WSPs and polyester film sampling plates, analyzed the images of WSPs using the SigmaScan 5.0 software, measured the deposition amount of the tracer solution using the Analyst 600 spectrometer, and quantitatively evaluated the relative deposition amounts of the deposition and drift sampling points. Their results demonstrated that the deposition amount of glyphosate spray measured using the combination of the two methods was consistent. Wen et al.[20] collected the droplets of Rhodamine B solution sprayed in the field using WSPs and polyester film cards, analyzed the images of WSPs using the DepositScan software, measured the eluent concentrations using the F-380 fluorescence spectrophotometer, and calculated the deposition amount of spray droplet. Lou et al.[21] collected the spray droplets using the Kromekote cards and filter papers. The images of these cards was analyzed using the Image J software, and the spray droplet density and coverage was calculated. The eluent solution after eluting the filter papers was measured by using the ELISA instrument, and the deposition amount of spray droplets was calculated. The spray droplet distribution and drift characteristics during the UAV spraying process was analyzed.

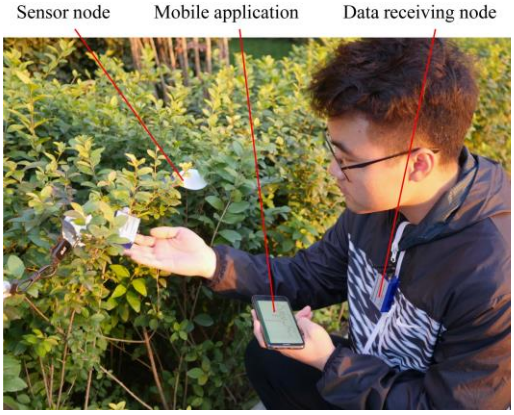
2.4 Application of electronic information technology in sampling analysis technologies

With the development of electronic information technology, researchers have developed electronic sensors for rapidly measuring droplet deposition, to improve the efficiency of droplet deposition measurement and analysis. The sensors are based mainly on the principles of the variable dielectric constant capacitor, inductive sensor, variable-conductivity resistance sensor, and variable light transmittance optical sensor. Salyani et al.[22] designed a spray liquid deposition sensor based on the principle of variable resistor. They also established the relationship models between the sensor output voltage and spray deposition amount when using tap water, NaOH solution, and NaCl solution as the spray liquid. Crowe et al.[23] developed a sensing device for measuring the deposition distribution of spray droplets, which has a plurality of small hole arrays on the surface, where the center of each small hole is equipped with a conductive pad. When the spray droplets are deposited in a small hole, the output voltage varies and the corresponding LED emits light. The density of droplet deposition is then reflected by the number of lighted LEDs. However, the testing performance of this sensing device is related to the droplet size. Specifically, the testing performance for coarse droplets is the most optimal. Based on the principle of the variable dielectric constant capacitor and sensor network technology, Zhang et al.[24] designed a real-time monitoring system for the ground deposition of aerial spray droplets and investigated the system's practicability for measuring the ground deposition of spray droplets. The relative error of the system was observed to be in the range of 10%-50%. The testing node for spray liquid deposition based on the capacitance sensor is shown in Figure 5.

Melissa et al.[25] developed a resistor-based electronic sensor array and data acquisition system for measuring the spray deposition of hydraulic nozzles, and analyzed the effects of the liquid's temperature and droplet spraying angle on the sensor output. Wu et al.[26] proposed an interdigitated droplet collecting plate structure based on the principle of standing wave rate, for testing deposition amount. They established a regression model for the relationship between the output voltage of the testing system and the deposition amount of the reagent solution. The model's accuracy attained values above 0.98. Sun et al.[27] developed a system based on the theory of solution conductivity. They studied the relationship between the droplet deposition amount and the solution conductivity to achieve the rapid measurement of spray deposition quality. A comparison between the measurement results using their developed system and the paper cards showed a relative error of less than 7.75%. The droplet collection and recovery rates of the system were 84% and 91%, respectively. Based on the LWS-type foliar humidity sensor (functioning on the principle of the variable dielectric constant capacitor), Yang et al.[28] designed a testing system of droplet deposition on fruit tree leaves for the low-level spraying of plant protection UAVs. They obtained the droplet deposition density on the leaves after the spraying operation by the WSZ-4X-type plant protection UAV in an orchard. A comparison with the results obtained using WSP showed that the fitting degree of the two deposition curves could attain 0.92. Dieter et al.[29] evaluated the feasibility of a commercially available foliar humidity sensor for measuring spray droplet deposition and coverage in real time through experiments. By comparing with WSP measurement results, they observed that the sensor output voltage signal and coverage were significantly correlated. This established that the system could be applied for online deposition measurement.



a. Sensor node ①



b. Sensor node ②

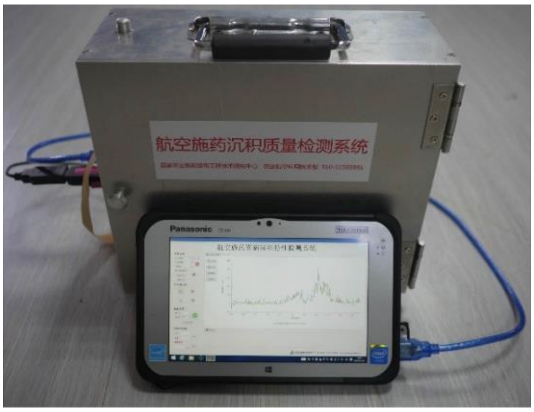
Figure 5 Testing node for spray liquid deposition based on the capacitance sensor

The testing method based on the variable dielectric constant capacitance sensor requires the sensor surface to be cleaned each time before spraying, which makes it inapplicable for multiple continuous measurements. When the amount of droplet deposition is large, the droplet tends to slip off the sensor, thereby affecting the measurement accuracy. Furthermore, it can only measure one deposition effect index relatively well, and is not capable of acquiring other deposition distribution parameters (such as droplet deposition point density or particle size distribution).

Currently, research on the online rapid testing technology in the field is still relatively inadequate. A few scholars have designed and developed new testing systems, which can improve the accuracy, enable convenient field testing for testing droplet deposition characteristics, and provide real-time feedback for spraying decisions, so as to achieve a better spraying effect. To test deposition patterns and quantify the amount of deposit in a continuous way, the measurement of spray deposition was also attempted at a early time. A system which utilized a fluorescent tracer solution and sprayed onto the surface of a continuous paper collector was developed by Liljedahl and Strait[30]. Specialized door attached to a fluorometer was manufactured to test and measure fluorescent tracers concentrations absorbed by the string and paper collectors[31]. A string deposition analyzer (Figure 6) was used to determined the fluorescence level of rhodamine B (WT) collected on the cotton string during hover spraying[32].

However, the collection efficiencies of droplet deposit collector was depend on the structures and shape of the collector, meanwhile, the testing accuracy of droplet deposition was determined by data processing method and resolution of measurement system. So a UAV spraying deposit pattern measurement system[33-34] was designed and developed based on spectral analysis and fluorescence tracing to measure spraying deposit pattern in a continuous way and improve the testing accuracy of droplet deposition synchronously, the system as shown in Figure 7.

Figure 6 The WRK string analysis system detecting fluorescence level of rhodamine B (WT)



a. Hardware device of the system

b. Software interface of the system

Figure 7 Testing system for deposition characteristics of aerial spray droplets

3 Laboratory simulation analysis technology

Traditional field tests are constrained by many factors such as complex test environment, low test repeatability, low spatial and temporal resolution of measurement methods, and high test costs. To address these shortcomings, researchers have developed various indoor testing techniques as a supplement to field tests. A few of these testing techniques can provide unique test data.

The initial droplet size distribution data of spray droplets generated by an aerial nozzle is obtained mainly by simulating the actual flight environment in a high-speed wind tunnel. This is followed by measurement with a laser particle size analyzer. The particle size of spray droplets and dynamic aerosols are measured in real time using a laser particle size analyzer. The main brands include Malvern Spraytec (U.K.), Sympatec HELOS (Germany), and Oxford Laser (U.K.)[35-37]. These are shown in Figure 8.

This type of device measures the particle size by analyzing the spatial distribution of the light diffraction spectrum caused by the particles. It can rapidly test the droplet size distribution for dense spray areas, and the droplet size measurement range can attain 0.5-3500 μm. At present, USDA-ARS, the University of Nebraska, and the University of Queensland have equipped their high-speed wind tunnels with laser particle size analyzers to test various types of aerial nozzles on manned aircrafts[38-40], these are shown in Figure 9. In china, South China Agricultural University and Nanjing Institute of Agricultural Mechanization have also built their own wind tunnels for agricultural aerial spraying.

The construction of the wind tunnel laboratory for agricultural aerial spraying located at the National Research Center of Intelligent Equipment for Agriculture (NRCIEA, China) began in 2014, and was completed and officially put into use on June 2015. The laboratory has an open and a closed wind tunnel. The experimental segment of the open tunnel has a caliber of 300 mm and a stable wind speed of 6.7-98 m/s. The experimental segment of the closed tunnel has a caliber of 600 mm and a wind speed of 3-45.7 m/s. The laboratory were equipped with a HELOS-VARIO particle size analyzer (SYMPATEC, Germany) and a Spraytec particle size analyzer (Malvern Panalytical, U.K.), which can perform high-precision particle size spectrum analysis and research. It is also equipped with a laser phase Doppler interferometer (PDI-200, Artium, U.S.) and a particle image velocimetry system (PIV/PLIF, LaVision, Germany). The wind tunnel experiment system is shown in Figure 10.

The PDI system adopts an optical system composed of a diode-pumped solid-state (DPSS) laser, and uses the laser phase Doppler effect to measure the droplet size and velocity of passage through the laser focus. It has a particle-size measurement range of 0.3-7000 μm and a velocity measurement range of –100-300 m/s. This method has been widely used in the measurement of spray particle size and velocity distribution of various nozzles[41]. The NRCIEA research team used this test platform to measure the initial droplet size and velocity distribution generated by the commonly used flat fan-shaped nozzles of agricultural UAVs. They also introduced the results into a three-dimensional (3D) numerical model, which provided an initial spray parameter support for predicting droplet movement, deposition, and drift[42]. The corresponding experiment setup and results are shown in Figure 11.

The PIV technology is based on laser planar particle imaging, which obtains the instantaneous velocity field of flow by performing correlation calculation on the time series of particle images. It is applicable for low- to high-speed velocity/vorticity field measurement, aerodynamic analysis, two-phase flow research, and particle analysis. The time-resolved PIV analysis, which involves the use of high-speed lasers and high-speed CMOS cameras, can provide flow field information with high-spatial-temporal precision. With regard to spray measurement, PIV technology can directly obtain the spatial distribution of the spray droplet velocity of a flat fan nozzle[43]. Measurement of initial spray velocity distribution of Lechler nozzle LU120-02 based on PIV is shown in Figure 12. This can serve as a supplement to the PDI measurement technology.

a. Malvern Spraytec b. Sympatec HELOS c. Oxford Laser

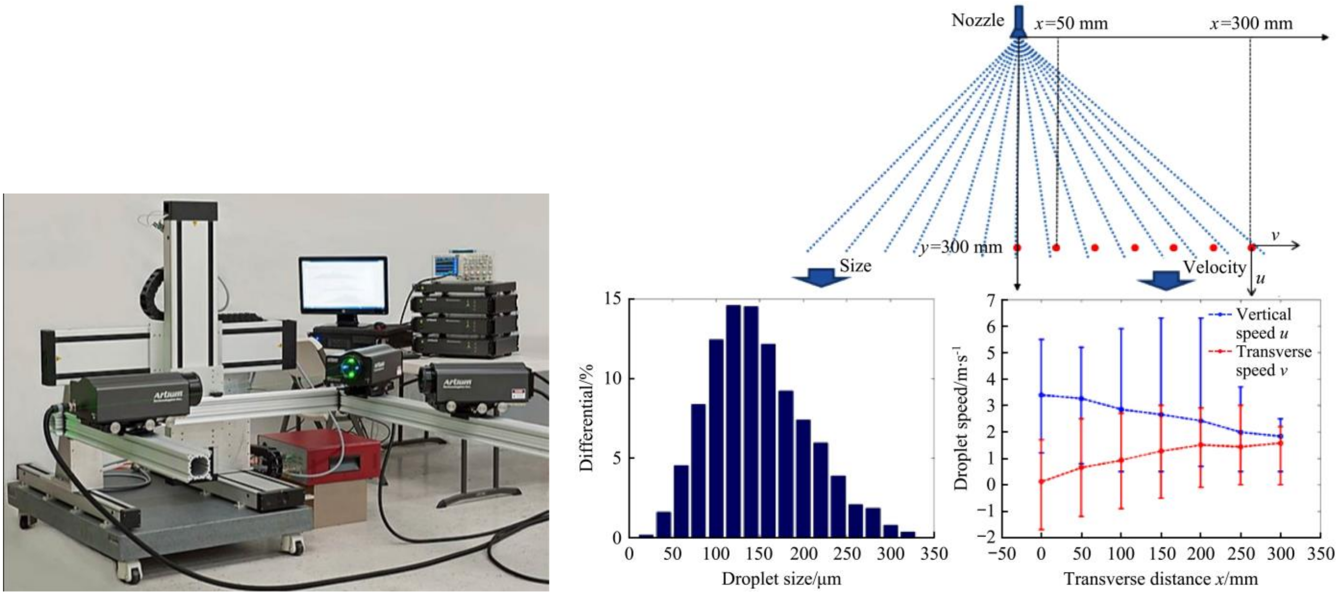
Figure 8 Main brands and models of laser particle size analyzer

a. USDA-ARS high-speed wind tunnel b. Wind tunnel for spraying-experiment at University of Nebraska c. Wind tunnel for spraying-experiment at the University of Queensland

Figure 9 Installation and application of laser particle size analyzers in wind tunnels

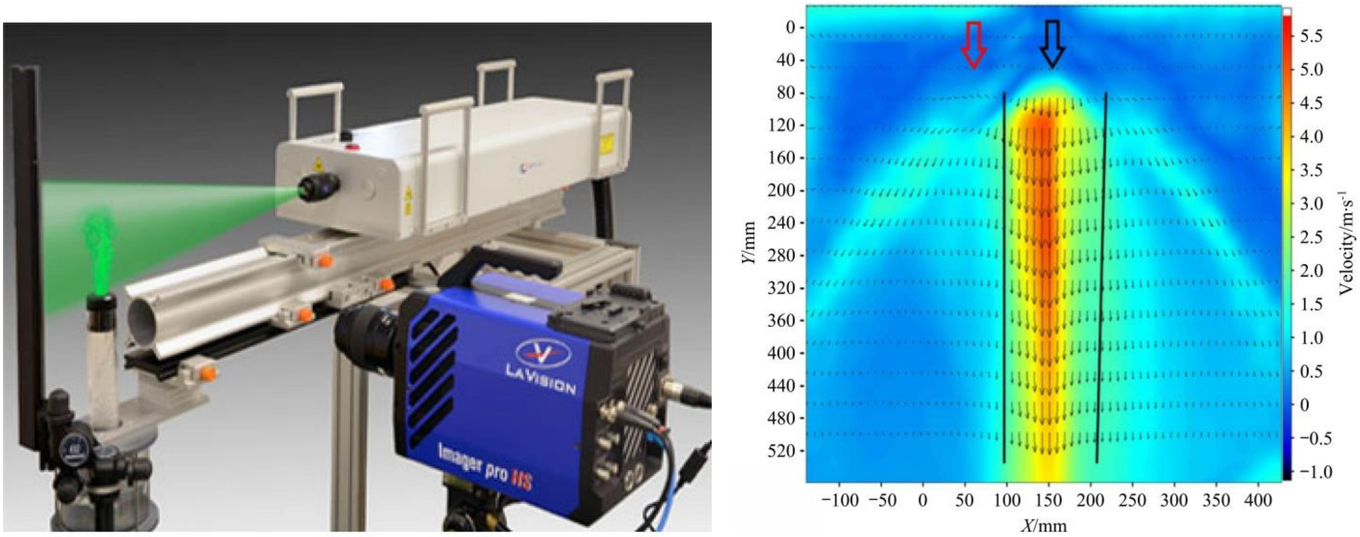
a. IEA-I wind tunnel b. IEA-II wind tunnel

Figure 10 Wind tunnel experiment system at NRCIEA in China



a. Phase Doppler Interferometer b. Initial droplet size and velocity distribution

Figure 11 Measurement of initial spray velocity and particle size distribution of ASABE standard fan nozzle 11001 based on PDI



a. Particle image velocimetry b. Droplet velocity field

Figure 12 Measurement of initial spray velocity distribution of Lechler nozzle LU120-02 based on PIV

4 Computational modeling simulation analysis technology

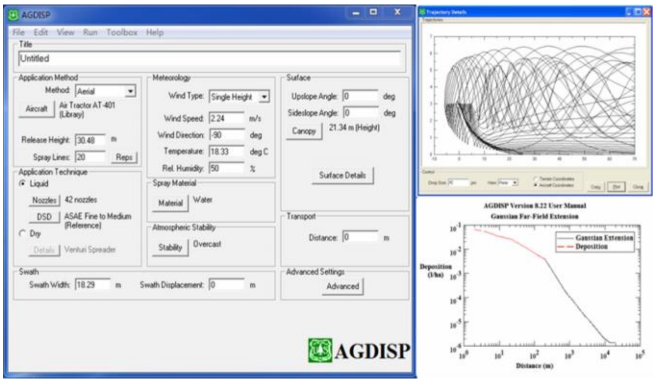
The deposition and drift of agricultural aerial spray are affected by many factors such as the environmental wind field, flight height, flight speed, droplet size spectrum, nozzle configuration, and weather conditions[44-47]. Currently, no universal computing simulation model is available. Rather, the computing model selected depends on the research object. The most commonly used models include the Gaussian plume, Lagrangian, statistical, and computational fluid dynamics (CFD) models.

4.1 Gaussian plume model

The Gaussian plume model describes the shape of the spray and distribution of droplets in it, using an exponential function. It is used mainly to simulate the long-distant (0.5-10 km) transportation of point-source, line-source, and area-source sprays in the atmosphere, while considering the influence of atmospheric stability. The U.S. Environmental Protection Agency calibrated the relevant parameters in the model using a large amount of experimental data. They then applied the model to predict the drift and deposition of aerial spray droplets[48], thereby assisting the formulation of spraying programs and delineation of buffer zones where spraying is prohibited. However, the Gaussian plume model does not consider the effect of aircraft wake vortex or the evaporation of droplets. It also omits the atomization process of the spray liquid and the movement of droplets when they exit the nozzle. Therefore, it is unsuitable for simulating the close-range movement and deposition of droplets under the influence of wake vortex near the aircraft. Since 1971, the USDA Forest Service has transformed the Gaussian model used by the military to predict the drift of spray droplets in forestry pesticide application. The results have shown a relatively good agreement between the model prediction values and experimental values[49]. Subsequently, Grim and Barry developed an algorithm to simulate the deposition of spray droplets on a forest canopy[50]. Then, Dumbauld et al. ported the algorithm to the Gaussian model[51], which has played an important role in guiding the actual application of pesticides. This model has been developed into the Forest Service Cramer–Barry–Grim (FSCBG) model by incorporating models for the penetration of spray droplets, effect of aircraft wake vortex, and evaporation of spray droplets[52-53]

4.2 Lagrange model

The Lagrangian model solves the spray transport process directly. However, for factors that affect the transport of spray droplets (such as air movement and spray evaporation), a parametric method is adopted for the description. There are many Lagrangian models such as the random-walk model, ballistic (spray droplet trajectory) model, and agricultural dispersion (AGDISP) series models. In 1979, National Aeronautics and Space Agency (NASA) began to study the Lagrangian model for describing the motion of droplets. Teske developed the WAKE software in his research on aircraft vortex at NASA[54-55]. It is used for calculating the movement and attenuation of aircraft vortex under the influence of the atmospheric boundary layer and ground. Subsequently, Bilanin and Teske[56-57] developed the AGDISP software (Figure 13) based on WAKE, which combined the Lagrange equation of droplet motion proposed by Reed and considered the evaporation of droplets. Through this model, users can input operating parameters such as nozzles, spray material, aircraft types, and meteorology factors, and call the internal database to predict the droplet deposition and drift, estimate the droplet size parameters, and adjust the spray equipment performance. Thereby, it enhances the effect of controlling the spray drift[58-65]. The algorithmic development of AGDISP is ongoing[66]. Compared with the Gaussian plume model, the Lagrangian model represented by AGDISP is more suitable for simulating the problem of drift and deposition in the wake-affected area near an aircraft (<0.5 km).



Title: Untitled

Application Method
Method: Aerial
Aircraft: Air Tractor AT-401 (Library)
Release Height: 30.48 m
Spray Lines: 20

Application Technique
● Liquid
Nozzles: 42 nozzles
DSD: ASAE Fine to Medium (Reference)
○ Dry
Details: Venturi Spreader

Meteorology
Wind Type: Single Height
Wind Speed: 2.24 m/s
Wind Direction: -90 deg
Temperature: 18.33 deg C
Rel. Humidity: 50 %

Spray Material
Material: Water

Atmospheric Stability
Stability: Overcast

Surface
Upslope Angle: 0 deg
Sideslope Angle: 0 deg
Canopy: 21.34 m (Height)

Transport
Distance: 0 m

Swath
Swath Width: 18.29 m
Swath Displacement: 0 m

Advanced Settings

Figure 13 AGDISP software operation interface and simulation results

4.3 Statistical model

Unlike the models listed above, a statistical model is constructed upon the experimental data, and not concerned with the physical processes and mechanisms underlying the phenomenon. Therefore, the conclusions drawn from a statistical model are applicable only to the experimental conditions covered by the source data, and cannot be used to predict results outside this scope.

The AgDRIFT model also contains a few statistical models that are composed of the experimental results under the most extreme conditions in the SDTF. The intermediate values are obtained by interpolation[67]. Zhu et al.[68] developed the DRIFTSIM model based on a large number of CFD simulation results. However, the calculation of CFD consumes excessive time. Moreover, the threshold of use is high, which makes it inaccessible to the general aerial pesticide applicators. Therefore, Zhu et al. calculated a large number of results in advance, sorted it into a database, and then called the database through the DRIFTSIM program to predict the spray drift. Statistical models are generally used for describing the droplet size distribution[69], and they are usually obtained from the regression analysis of experimental data. The SDTF model contains a large amount of experimental data of droplet particle size for different nozzle types and spray liquid compositions. The DropKick model was developed based on these data[70].

4.4 CFD model

The CFD model solves the Navier–Stokes equation to calculate the motion of air, and then combines the Lagrangian method to solve the motion of spray droplets. However, it is difficult to obtain analytical solutions for the Navier–Stokes equation. Therefore, numerical methods are generally used to solve the Reynolds Averaged Navier–Stokes (RANS) equation.

In recent years, with the development of computer technology (particularly, multi-core CPU parallel computing and GPU parallel algorithms), it has become possible to directly simulate the droplet motion by CFD, particularly under complex flow field conditions[71-78]. However, there are relatively few studies on the spray drift of fixed-wing aircrafts. To date, the research teams from only the University of New Brunswick (UNB), Canada, and the NRCIEA, China, have simulated the droplet movement and deposition characteristics of Thrush510G and AT802 under operating conditions, using CFD[79-82]. The UNB team used the RANS model in conjunction with the "packets" particle model of the CFX commercial software, and constructed a 3D calculation domain (41×105×263 m) with the aircraft body as the fixed reference system. They also calculated the motions of spray droplets from an AT802 fixed-wing aircraft equipped with the AU4000 rotary atomizer, and obtained a relatively accurate aircraft wake movement (which considered the influence of the fuselage and propeller) as well as the resulting droplet movement law (Figure 14). However, this method is limited by the amount of calculation and numerical dissipation, and therefore, can calculate only the movement of droplets within a few seconds after being sprayed. In an actual operation, the drift process of spray droplets generally lasts up to tens to hundreds of seconds. Therefore, this solution cannot fully satisfy the actual application requirements.

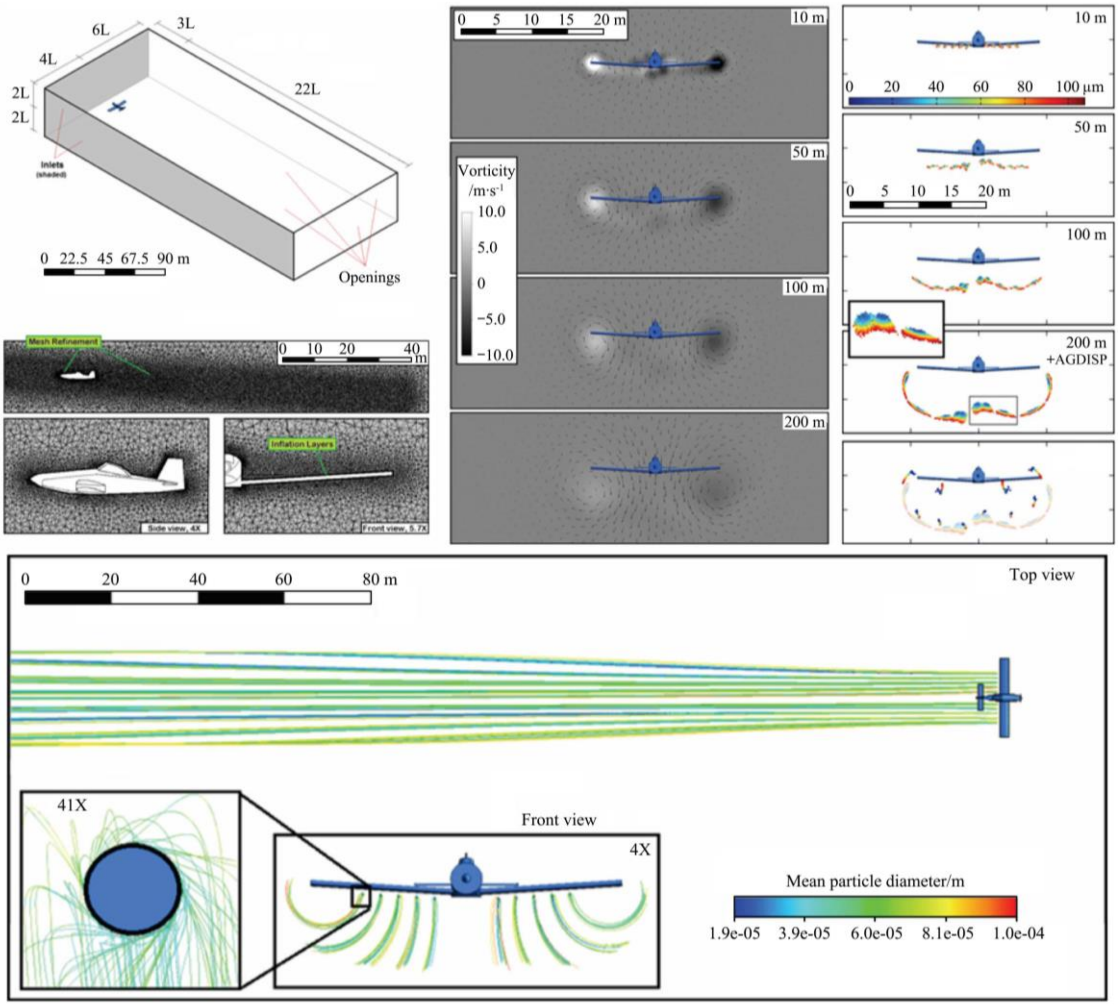
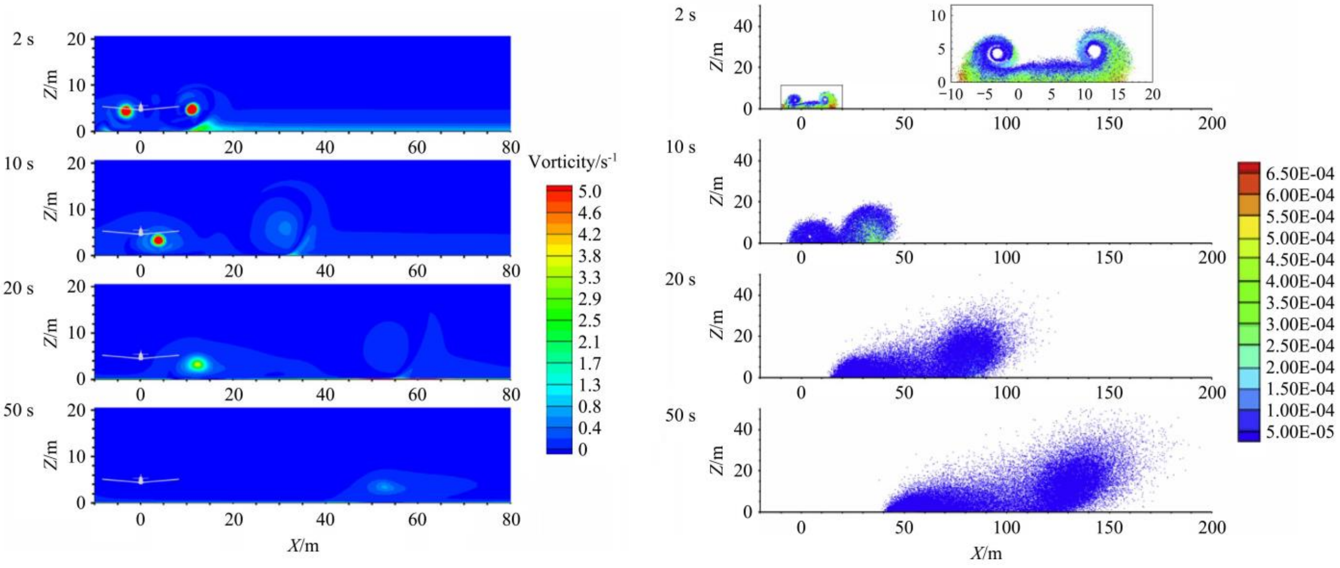


Figure 14 Movement law of spray droplets from a fixed-wing aircraft calculated using 3D CFD

Meanwhile, based on the fixed-wing aircraft wingspan, take-off weight, flight speed, and other specific parameters, the NRCIEA team simplified the problem in two dimensions (2D) by considering the ground as the fixed reference system. Furthermore, they directly constructed the initial wake vortex of the fixed-wing aircraft. This simulation method reduced the streamwise dimension and expanded the spanwise dimension. It captured the principle factors of the physical model (environmental wind field, wake vortex produced by the wing), omitted the secondary influencing factors (disturbance generated by the fuselage/propeller/empennage), and finally simulated the movement and dissipation of wake vortices over large spatial- and long time-scales with relatively low computing resource overhead[81-82]. The corresponding simulation results are shown in Figure 15.

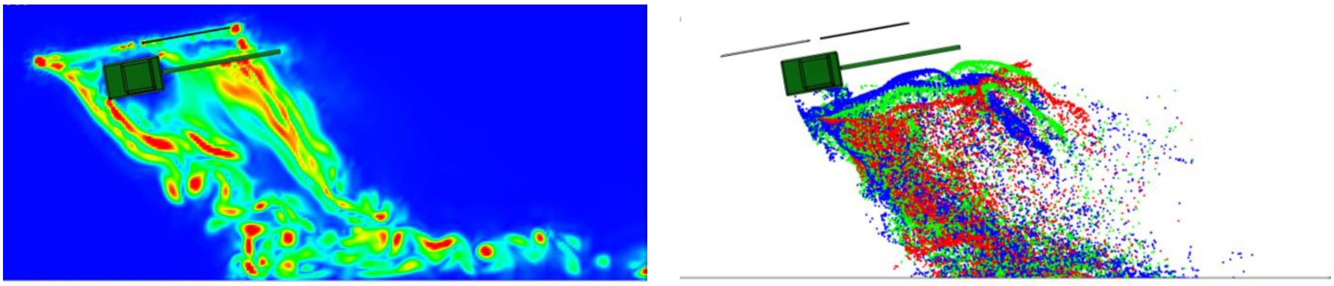
As the application of plant protection UAV was growing fast in recent years, the NRCIEA team also developed CFD model of UAV spraying[42]. The lattice Boltzmann method was used to simulate the movement of droplets sprayed by UAV, as shown in Figure 16.



a. Development of wing tip vortices

b. Droplet movement and spatial distribution

Figure 15 Fixed-wing aircraft wake vortices and spray droplet movement process simulated using 2D CFD



a. Vorticity distribution

b. Droplet movement

Figure 16 Movement law of spray droplets from a plant protection UAV calculated using 3D CFD

Overall, the CFD method has exhibited potential for accurately simulating the physical process of spray drift, as well as evaluating and improving traditional engineering prediction models. The cost of CFD simulation is substantially lower than that of the flight and wind tunnel experiments. With the advancement of computer and numerical calculation technology, the CFD method is expected to transform from a research tool for researchers, to a practical tool for pesticide applicators to plan pesticide applications, as well as for environmental supervisors to evaluate the effects and hazards of operations.

5 New analysis technologies

In recent years, with the development of non-contact remote sensing technologies, the real-time acquisition of spray droplet deposition and drift is becoming a new trend. Wang et al.[83] applied laser imaging technology to evaluate the total drift in a wind tunnel. This method used image acquisition, image denoising, and feature parameter extraction to achieve the final evaluation of the drift potential. Zhang et al.[84] measured the temperatures of crop canopy before and after the spraying operation by a plant protection UAV with an infrared thermal imaging camera. They used the temperature variation rate to ascertain the deposition effect of spray droplets on the canopy. Their results showed that the deposition amount obtained using this method was consistent with that obtained using a conventional testing method. Moreover, it could accurately reflect the spray droplet deposition effect on the canopy. Zhang et al.[85] studied the method for analyzing the deposition efficacy of spray liquid based on ground NDVI spectral reflectance measurements.

LIDAR is a non-contact remote sensor that has been widely used in the agricultural field. Many scholars have applied this emerging testing method to research pesticide drift. In 1989, Hoff et al.[86] applied LIDAR to pesticide application monitoring for the first time. The measurement target in their study was the pesticide spray movement in the wingtip vortex of a pesticide application aircraft. In 1997, Stoughton et al.[87] became the first to test the downwind drift of aerial spray by using LIDAR. In their experiment, the drift estimates calculated using the FSCBG and

UCST models were compared with the LIDAR scan data. Miller et al.[88] developed a LIDAR measurement system for testing pesticide spray droplets and applied it to measure the droplets in the air while spraying an orange orchard. Their experimental results verified the feasibility of this method for evaluating spray drift in the air in the field environment. Gil et al.[89] applied LIDAR to the testing of spray drift from vineyard sprayers, explored the influences of the sprayer air volume and droplet size on the testing effect, and compared the results with that obtained using a conventional testing platform. Their results showed that LIDAR exhibited a better testing effect when the air volume and droplet size were small. Zhang et al.[90] explored the use of LIDAR multilayer laser scanning technology for spray testing in the IEA-II wind tunnel at the NRCIEA, established the relationship model between the laser cumulative echo quantity and spray drift, and developed a data processing system for spray drift testing based on this relationship model, which is shown in Figure 17.

Zheng et al.[91] proposed a droplet testing method based on the principle of LIDAR reflection and developed four algorithms, one each for target recognition and extraction, time-domain superposition, effective distribution range calculation, and 3D distribution modeling. Their experimental results showed that the relative error of the measurement was less than 7% and standard deviation of the loudness was less than 16% compared with the manually measured values. This demonstrated the applicability and accuracy of the 3D model. Gregorio et al.[92-94] conducted a series of studies on the testing of spray drift in the air with LIDAR sensors. They established a correlation analysis model between the traditional passive testing and LIDAR-based testing through continuous experiments. On this basis, his team developed a laser measurement system (Figure 18) that is safer for the human eye and assessed the spray drift potential reduction for nozzles[95]. The LIDAR-based testing technology uses the time of flight (TOF) principle. When the laser hits the droplet cloud and is reflected, the laser receiver calculates the distance and position information of the droplet cloud through TOF and generates the 3D point cloud coordinates of the spray droplets. This method can obtain information on the drift amount of spray liquid as well as output the drift distance. This has important guiding significance for establishing spray application buffer zones.

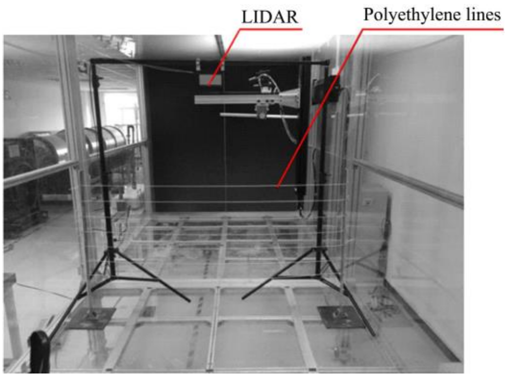


Figure 17 Development of spray drift predict model with LIDAR in wind tunnel

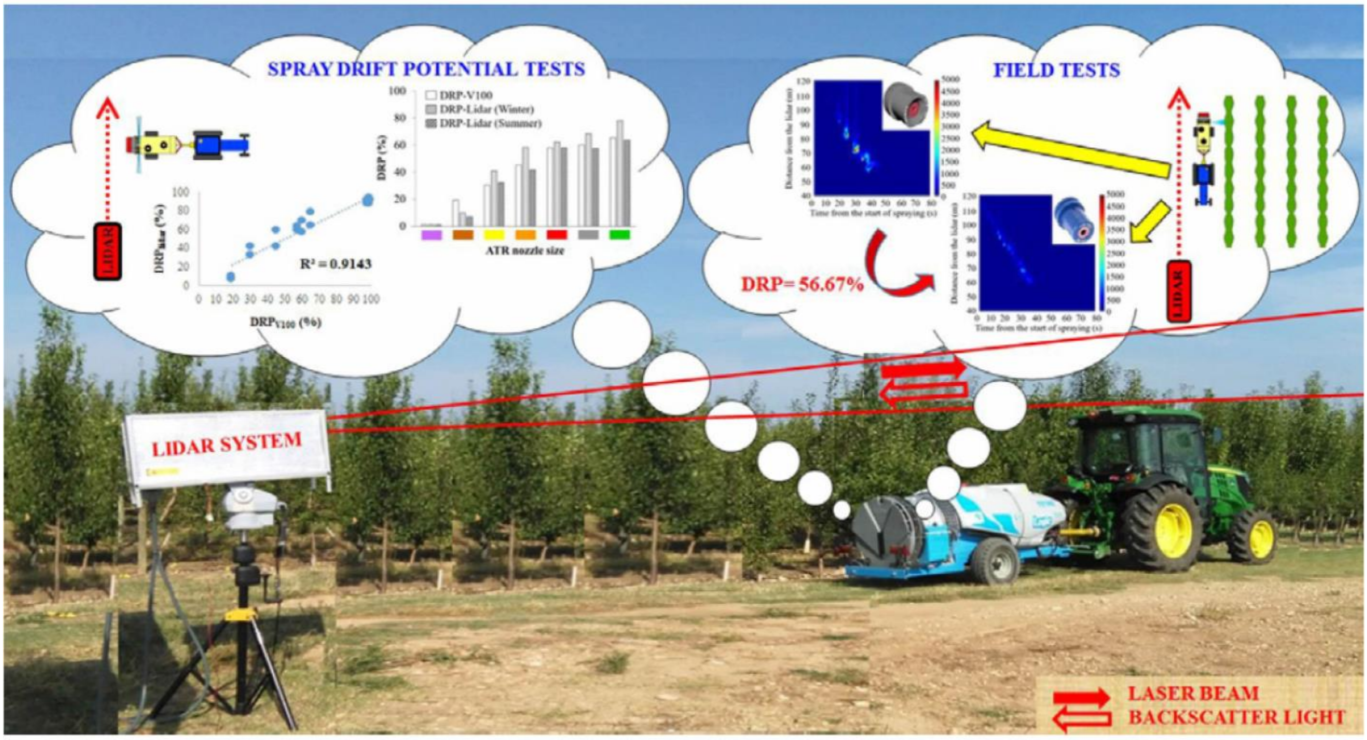
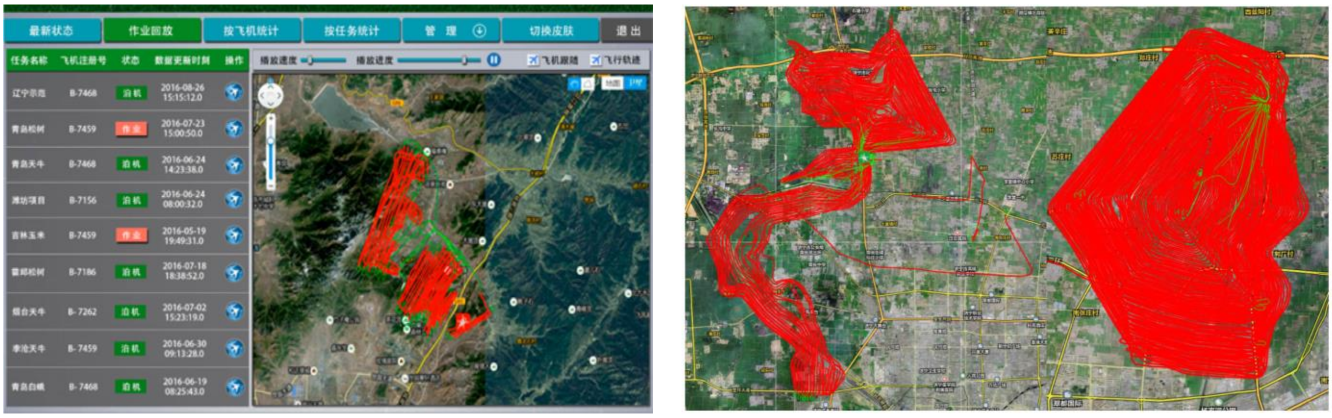


Figure 18 Spray drift of orchard sprayer tested by LIDAR system

Remote optical spectroscopy has also been widely used in the drift testing of pesticide spray droplets. Its underlying principle is the testing of chemical substances in the atmosphere. Relevant research in this area has been conducted relatively early in the Beijing Research Center for Information Technology in Agriculture, China. Zhao et al. developed a telemetering system and method for testing the distribution and drift trend of aerial sprays. They obtained the infrared imaging spectrum of the testing area distributed with chemical spray clouds by using infrared radiation, and performed feature analysis to predict the drift trend of spray[96]. Zhang et al.[97] developed a system and method for monitoring the drift tendency of aerial spray. Their system can monitor the drift tendency of spray droplet cloud in real time through the laser information reflected by the spray droplet cloud. There are also other optical spectral testing technologies: For example, differential optical absorption spectroscopy[98] and tunable diode laser absorption spectroscopy[99] use the UV–VIS and VIS–NIR–MIR wavelengths, respectively. Similar to the method described above, open path Fourier transform infra-red (OP-FTIR) spectroscopy is relatively more commonly used for the research on pesticide drift testing. This technology adopts the NIR–MIR band. The measurement device is equipped with a locator and multiple reflective light sheets. The tomography and mathematical inversion methods are used to test the pesticide drift. Kira et al.[100] verified the feasibility of OP-FTIR technology for testing the drift of spray droplets experimentally. Based on this, they[101] further clarified the spectral characteristics of pesticide organic compounds that could be effectively tested using this technology through experiments. This laid the foundation for its practical applications. Non-contact remote testing technologies have strong real-time characteristics and high testing efficiency. However, their testing accuracy is closely related to the droplet size distribution. The main challenge of these technologies is the quantitative calibration of the return signals and the air plume. In addition, they have relatively high requirements of meteorological conditions during the testing process. Various research institutes have applied for patent protection for these new technologies. Most of these are still in the experimental stage and not suitable for actual applications. It is expected that the above-mentioned new testing technologies can be used in practice to improve the capability for real time drift testing and reduce the consumption of human and material resources during the testing process.

The NRCIEA developed an airborne acquisition system of pesticide application parameters applicable to various types of manned and unmanned plant protection aircrafts[102]. This system is shown in Figure 19, and it integrated a GPS module, an attitude sensor, a flow sensor, a pressure sensor, an altimeter, and a communication module. These can monitor the aircraft attitude, position, altitude, as well as the pressure and flow information during operation, in real time. These parameter data can then be input into the prediction model for aerial spray drift and deposition to calculate and analyze the drift and deposition area of the spray liquid during the application process, in real time. Since the installation of this system in 2013, it has been applied to 18 mainstream aircraft models for agricultural and forestry aerial pesticide application operations in China. These covered a cumulative service area of over 90 million mu. This system has provided a practical real-time analysis method for aerial spray drift.



任务名称	飞机注册号	状态	数据更新时间	操作
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青岛松树	B-7459	作业	2016-07-23 15:00:50.0	
青岛天牛	B-7468	泊机	2016-06-24 14:23:38.0	
潍坊项目	B-7156	泊机	2016-06-24 08:00:32.0	
吉林玉米	B-7459	作业	2016-05-19 19:49:31.0	
[illegible]	B-7186	泊机	2016-07-18 18:38:52.0	
烟台天牛	B-7262	泊机	2016-07-02 15:23:19.0	
李沧天牛	B-7459	泊机	2016-06-30 09:13:28.0	
青岛白蛾	B-7468	泊机	2016-06-19 08:25:43.0	

a. Interface of the aviation application supervision platform

b. The application route

c. Airborne equipments

d. Installation and application

Figure 19 An airborne acquisition system of pesticide application parameters

6 Main challenges and future trends

6.1 Main challenges for the technologies for analyzing aerial spray deposition and drift

Researchers worldwide have conducted many studies on and improved the traditional sampling testing and analysis technology for measuring aerial spray drift. However, the current sampling method based on WSP images and fluorescent tracer eluent is time-consuming, cumbersome, and has insufficient accuracy. The method based on electronic sensors can have only one monitoring index, and the droplet deposition collector’s collection efficiency is dependent on its structure and shape. In addition, the accuracy is largely determined by the data processing method and sensor resolution. With the development and application of UAV technology, the deposition of spray droplets from agricultural UAVs is affected by the complex downwash flow field of the rotor. Furthermore, the spatial distribution of droplets is significantly different[103]. The sampling methods using sensors, WSP, and sampling cards are discrete, which cannot objectively and accurately reflect the droplet deposition distribution on the target. Furthermore, the ultra-low-volume spray technology applied in the field of plant protection UAVs has higher requirements and challenges for the efficiency and accuracy of the testing method. Therefore, in the research and development of highly real-time and precise testing instrument, the reduction in the cost of the widespread application of the instrument in the agricultural field remains a major challenge encountered by the traditional sampling-based testing and analysis technologies for spray deposition and drift.

The main issues of indoor experimental technologies include the difficulty of restoring the actual operating environment and the intrinsic measurement limitations of the experimental instrument. For example, it is not realistic to restore the operating environment of a manned aircraft at the scale of a wind tunnel. Rather, only the initial spray droplet distribution of an aviation nozzle can be measured. Therefore, in such a case, where the actual operating conditions cannot be fully restored, indoor experiments should focus on providing reliable data under limited conditions. For example, although the initial droplet distribution of an aviation nozzle based on high-speed wind tunnel measurements does not yield a comprehensive spatial and temporal distribution of droplets, it can provide the initial condition of droplet distribution to support the numerical simulation. Meanwhile, optical measurement methods such as PDI and PIV have their limitations. PDI focuses on single-point measurement, which requires a point-by-point scanning when spraying on a large area. However, this approach is applicable only to steady spray and not to unsteady spray droplet movement under the influence of the wind field of a plant protection UAV. PIV can measure the evolution of an unsteady flow field in a certain range. However, it is limited by the test space range and tracer particle size, and there are certain difficulties in testing the structure of a wind field over a 1 m scale. To address the above problems, effort should be undertaken to improve the applicability of the experimental instrument; develop new experimental instrument; or expand the scope of experiments that can be performed using the existing instrument, such as develop large-scale PIV and high-frequency scanning PDI. In addition, the characteristics and advantages of the existing instrument should be fully leveraged to provide initial conditions, boundary conditions, and references to simulation results to the extent possible through combination measurement and verification measurement methods. The limited albeit sophisticated indoor experiment technologies should be utilized fully to effectively support the field experiments.

Notwithstanding the large variety of drift deposition models and different methods, the main challenge is the contradiction between the simulation accuracy and required computing resources. Considering the CFD model (the method displaying the highest potential for becoming the mainstream in the future) as an example, to accurately simulate the aerial application process, a highly precise calculation format or a high-density grid is required to capture wingtip vortices and other typical flow structures. However, these steps would incur a tremendous amount of calculation. In the future, the following improvements need to be achieved to solve these problems.

- Developing adaptive grid technology to reduce the number of non-essential regional grids, and thereby reducing the amount of calculation.
- Developing near-wall turbulence models so as to reduce the number of boundary layer grids required near the wall while ensuring the near-wall simulation accuracy.
- Developing a high-precision calculation format with good robustness to reduce the required grid quality and quantity.
- Developing GPU parallel algorithms, improving computing power of systems being used, and simulation algorithms suitable for GPU parallel computing.

6.2 Research priorities and development trends

At present, the mechanisms of spray deposition and drift are relatively well clarified. The use of advanced technologies to develop practical technical products and application systems is the main development trend of future key analysis technologies for aerial spray drift and deposition. The following research focuses are likely according to this trend:

(1) The use of optical or machine vision technologies for developing sensors and portable instruments for measuring spray deposition index to improve the analysis efficiency of spray deposition quality in the field and thereby, better serve agricultural production.

(2) The integrated development of aerial spray drift deposition and analysis technologies, special equipment for aerial spraying, and aircraft model processing and manufacturing industries. The production of aerial spraying equipment is a large processing and manufacturing industry. Compared with agricultural production, the processing and manufacturing industry has a higher scope for increasing capital investment and absorbing new technologies to improve product performance and functional indicators and thereby, promote the development of new analysis technologies for aerial spray drift and deposition.

(3) Further comprehensive application of CFD computational modeling, laboratory simulation, and statistical experiment in the field, as well as the construction of composite models. The long-term future development directions include the construction of computational models through theoretical models, correction and verification of the computational models through laboratory simulations, and practical parameter-tuning and perfecting of the models through specific statistical data acquired in the field.

(4) The application of artificial intelligence technologies such as machine learning and big data technology. Fundamentally, the analysis of aerial spray drift and deposition is the analysis of the motions of the spray droplets in the air. However, droplet motion has many influencing factors, which also exert interactive impacts on each other. It is rather challenging to decouple the numerous factors and then implement single-factor analysis and formulation modeling. Rather, sample data can be obtained through laboratory and field experiments as well as calculations (which eliminates the need for principle analysis), and by constructing drift and deposition analysis models with certain practicality, using machine learning methods.

7 Conclusions

This study has clarified the applicable research scenarios for different technologies after exploring and analyzing the research status quo as well as the pros and cons of four types of key analysis technologies for aerial spray deposition and drift (namely, sampling, laboratory simulation, computer simulation modeling, and new analysis technologies). Notably, electronic technology, computer technology, and other information technologies are becoming more widely used in the analysis of aerial spray deposition. In addition, the instruments for rapidly measuring spray deposition in the field and the real-time accurate prediction models of spray drift are the most in-demand for the analysis of aerial spray deposition and drift. These have become the research hotspots in recent years. The use of advanced technologies for developing practical technical products and application systems is the main development trend of future key technologies for analyzing aerial spray deposition and drift. The four major research focuses include the development of sensors and portable instruments for measuring spray deposition index using optical and machine vision technologies; integration and development of the analysis technologies for aerial spray deposition and drift, special equipment for aerial spraying, and machinery processing and manufacturing industries; further comprehensive application of CFD modeling, laboratory simulation, and statistical experiment in the field, as well as the construction of composite models; and application of machine learning, big data technology, and other artificial intelligence technologies.

Acknowledgements

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