Research Advances in Key Technologies and Validation Methods for Numerical Modeling of Pesticide Application by Plant Protection UAVs: Postprint

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Abstract

With the increasing application of plant protection UAVs in precision agriculture, numerical simulation methods for the evolution of downwash wind fields and the resulting droplet deposition and drift processes have rapidly diversified. However, there remains a lack of systematic review of the advantages, disadvantages, applicability, and validation methods of each approach. This paper discusses inviscid models, computational fluid dynamics (CFD) models, and Lattice Boltzmann models separately. The inviscid wake vortex model based on the vortex element method has the advantage of simple computation, but due to the lack of viscosity and turbulence models, its simulation accuracy for droplet deposition and drift is relatively low. Computational fluid dynamics models are further divided into finite volume methods and finite difference methods. Among them, the finite volume method has high robustness and can be applied to simulations of various complex environments, but its scheme accuracy is limited, and the simulated wingtip vortex dissipation rate is much faster than in reality; the finite difference method can achieve high spatiotemporal accuracy in simulating wingtip vortex evolution, but it suffers from issues such as high requirements for grid structure and excessive computational demands. The Lattice Boltzmann method has advantages in computing three-dimensional flow field problems with complex boundary conditions and non-stationary moving objects, but it still has deficiencies in functional diversity and completeness. The accuracy of the aforementioned numerical models still needs to be validated and optimized through comprehensive field experiments and indoor experiments, such as high-speed Particle Image Velocimetry (PIV) or Phase Doppler Interferometry (PDI) methods. Finally, this paper proposes future development directions for plant protection UAV spraying simulation and validation methods.

Full Text

Preamble

ChinaXiv Cooperative Journal: Key Technologies and Verification Methods of Numerical Modeling for Plant Protection UAV Spraying

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Abstract: With the increasing application of plant protection unmanned aerial vehicles (UAVs) in precision agriculture, numerical simulation methods for the evolution of downwash flow fields and the resulting droplet deposition and drift processes have achieved rapid and diversified development. However, a systematic review of the advantages, disadvantages, applicable scopes, and verification methods of each approach is still lacking. This paper discusses inviscid models, computational fluid dynamics models, and lattice Boltzmann models. The inviscid wake vortex model based on the vortex element method offers computational simplicity, but suffers from low simulation accuracy for droplet deposition and drift due to the absence of viscosity and turbulence models. Computational fluid dynamics models are further divided into finite volume methods and finite difference methods. The finite volume method exhibits high robustness and applicability to various complex environments, but its limited scheme accuracy causes rotor tip vortex dissipation rates far exceeding realistic values. The finite difference method enables high spatiotemporal precision simulation of tip vortex evolution, yet faces challenges such as stringent structured grid requirements and excessive computational demands. The lattice Boltzmann method demonstrates advantages in computing three-dimensional flow fields with complex boundary conditions and non-stationary moving objects, but still exhibits deficiencies in functional diversity and completeness. The accuracy of these numerical models requires comprehensive validation and optimization through both field experiments and indoor experiments, such as high-speed particle image velocimetry (PIV) and phase Doppler interferometry (PDI). Finally, this paper proposes future development directions for plant protection UAV spraying simulation and verification methods.

Keywords: plant protection UAV; downwash flow field; numerical simulation; droplet deposition and drift; computational fluid dynamics

1 Introduction

Unlike ground-based operations, agricultural aerial spraying effectiveness is influenced by multiple factors including ambient wind fields, flight altitude, and speed [?, ?]. Predicting droplet drift and deposition based on current environmental wind fields and operational parameters, thereby enabling real-time adjustment of operational parameters, represents the implementation method and pursuit goal of precision agricultural aviation [?]. In the 1970s, as manned fixed-wing aircraft and helicopter spraying operations became widespread globally, NASA and the U.S. Air Force developed the AGricultural DISPersal (AGDISP) model for manned aircraft spraying drift prediction based on Lagrangian equations and Gaussian models, which has become a universally accepted droplet drift prediction tool. However, this model lacks direct simulation capability for atmospheric turbulence and cannot accurately simulate droplet movement and deposition under complex airflow conditions within aerial application swaths [?].

In recent years, with advances in computer technology, direct numerical simulation of droplet movement based on computational fluid dynamics (CFD) has gradually become possible, particularly for droplet movement patterns in steady flow fields. Current research primarily focuses on ground-based air-assisted spraying simulations with simple wind fields and spray structures, without involving droplet movement processes under complex unsteady rotor downwash flow fields. For example, Tsay et al. [?] conducted CFD simulations of air-assisted spraying processes under no-canopy conditions, while Delele et al. [?] and Dekeyser et al. [?] performed CFD simulations under canopy conditions to evaluate air-assisted spraying system performance under different operational parameters, thereby optimizing parameters, assessing spray drift characteristics, and reducing drift losses. Endalew et al. [?] conducted detailed numerical simulation studies on ground-based air-assisted sprayers, including model construction, airflow velocity distribution, effects of different sprayer types, and target canopy influences. Duga et al. [?] and Baetens et al. [?] simulated wind-driven droplet drift processes using three-dimensional CFD, considering combinations of drift-reducing and standard nozzles to avoid increased ground deposition losses while reducing drift distance.

With the explosive growth in plant protection UAV applications in precision agriculture, demands for spraying efficiency, quality, and potential environmental risk assessment have become increasingly prominent. However, droplet deposition and drift simulation started relatively late, faces significant research challenges, and has limited research quantity and accumulation compared to manned fixed-wing aircraft spraying studies, unable to meet the rapid growth of these demands. Therefore, this paper aims to review the current research progress in numerical simulation key technologies and verification methods for plant protection UAV spraying, analyze future development directions, and promote new breakthroughs in this field.

Currently, the main modeling approaches for plant protection UAV spraying research include: inviscid models, computational fluid dynamics models (including finite volume and finite difference methods), and lattice Boltzmann models. This paper summarizes the applicable scope, computational overhead, and simulation accuracy of these models, and proposes future optimization directions for each model. Additionally, this paper presents development suggestions for existing field and indoor experimental validation methods to improve high spatiotemporal precision unsteady flow measurement techniques and enhance model simulation accuracy, providing support for the development of plant protection UAV spraying simulation.

2.1 Inviscid Models

The most commonly used AGDISP software in aerial spraying droplet drift prediction is built upon inviscid equations. Since it does not directly solve the Navier-Stokes equations, it can only simulate droplet drift for simplified manned helicopter wake vortices, primarily through two-dimensional simplification of fixed-wing or manned helicopter trailing vortices to directly simulate two-dimensional vortex pair development near the ground. Although overall dissipation coefficients for wake vortices and diffusion coefficients for droplet clouds were added to account for viscous effects, the model still cannot accurately simulate droplet drift under complex three-dimensional flow fields generated by plant protection UAVs.

In 2018, Teske et al. [?] integrated a vortex element method-based inviscid wake vortex model (Comprehensive Hierarchical Aeromechanics Rotorcraft Model, CHARM) into the latest AGDISP droplet drift prediction model, solving AGDISP's inability to predict droplet deposition and drift for near-ground small multi-rotor UAV spraying operations.

2.1.1 Three-Dimensional Near-Field CHARM Model

The CHARM model, based on the vortex element method, was developed in the late 1980s. Its primary function is to simulate wake development, initially used to study the effects of military helicopter rotor airflow on aircraft carrier deck personnel, ordnance ballistics, and desert terrain dust generation. It integrates and improves upon most functions of early algorithms "RotorCRAFT" and "Evaluation of Hover Performance using Influence Coefficients (EHPIC)" [?], including rotor vortex lift surface models, source/dipole models for lifting/non-lifting surfaces, and a unique constant vorticity contour (CVC) full-span free wake vortex model [?, ?].

(1) CVC Model. The CVC model can simulate complex rotor tip vortex structures and their evolution. Instead of directly simulating the velocity field, it starts from the rotor rotation plane, distributes numerous vortex elements with constant strength throughout the flow field according to local vorticity distribution, and obtains the velocity distribution across the entire field through superposition of vortex-induced velocities. The vortex-induced velocity follows the Biot-Savart Law:

$$\mathbf{V} = \frac{\Gamma}{4\pi} \int \frac{d\mathbf{s} \times \mathbf{r}}{r^3}$$

where Γ is the vortex vector; $\mathbf{r}$ is the position vector; $d\mathbf{s}$ is the velocity vector; and r is the perpendicular distance to the vortex line (m). The CVC model automatically follows the Helmholtz/Kelvin law of total vorticity conservation, with tip vortex rotation radius unaffected by different flight conditions or aircraft models. However, it suffers from the inherent problem of inviscid point vortex models in their inability to simulate wake vortex dissipation and turbulence effects [**?**]. Its simulation results are shown in Figure 1 [Figure 1: see original paper].

(2) Rotor Vortex Lift Surface Model. The rotor vortex lift surface model is primarily used for simplified treatment of vortices on complex rotor surfaces. Currently, rotors can be represented by quadrilaterals composed of four constant-strength straight vortices. By assuming induced velocity at control points on each rotor quadrilateral, the rotor circulation is associated with vortex-induced velocity. Superimposing induced velocities from other vortices in the flow field yields the rotor constrained circulation. The Joukowski theorem is then applied to solve for rotor surface forces and moments.

(3) Lifting/Non-Lifting Surface Source/Dipole Model. For vorticity distribution problems caused by fuselage surfaces, the source/dipole simulation method for lifting/non-lifting surfaces is primarily used. The source strength is set to the normal component of the environmental flow, and dipole strength is adjusted to produce zero internal disturbance potential on the surface [**?**]. Surface velocity and pressure are obtained through finite difference of surface potential values, with wake plane position determined by estimating separation point location.

(4) Hierarchical Vortex Element Method Model. After CHARM development, it has been used multiple times for precise simulation of complete aircraft models in hover and forward flight conditions, gradually developing functions for multi-rotor wake simulation [**?**, **?**]. To improve CHARM simulation real-time performance, researchers introduced the Hierarchical Fast Vortex (HFV) method. When computing free vortex wake problems with N vortex elements, Central Processing Unit (CPU) computation per iteration grows at O(N^2) magnitude. The HFV method further divides the computational domain into different rectangular regions and uses octree networks to combine vortex elements in different regions based on influence coefficients, multipole expansion, and Taylor series expansion, reducing CPU computation per iteration from O(N^2) to O(NlogN) [**?**]. For a case with 35,000 vortex elements, the HFV method can reduce computation to 1% of the original algorithm, greatly improving simulation speed.

2.1.2 AGDISP Droplet Drift Model

The CHARM model primarily focuses on velocity field simulation within the three-dimensional near-field range of rotors. Due to the lack of viscosity and turbulence models, its simulation accuracy decreases significantly for far-field velocity simulation, and it does not involve droplet movement process simulation. Therefore, as a droplet drift model, AGDISP can complement CHARM to provide a complete solution for plant protection UAV spraying simulation. AGDISP employs relatively simple droplet motion models, primarily including near-field, far-field, and canopy motion simulations.

(1) Near-Field Simulation. For droplet drift and deposition simulation within 1000 m, AGDISP uses a Lagrangian-method-based droplet motion model, primarily considering gravity and aerodynamic drag effects on droplet movement while ignoring secondary forces such as added mass force, Saffman force, and turbulence effects. The simplified droplet force control equation is:

$$\frac{d\mathbf{X}_i}{dt} = (\mathbf{U}_i - \mathbf{V}_i)$$

$$\frac{d\mathbf{V}_i}{dt} = \frac{(\mathbf{U}_i - \mathbf{V}_i)}{\tau_p} + \mathbf{g}_i$$

where $\mathbf{X}_i$ is droplet coordinate (m); $(\mathbf{U}_i - \mathbf{V}_i)$ is gas-liquid velocity difference (m/s); $\mathbf{g}_i$ is gravitational acceleration (m/s^2); and τ_p is droplet relaxation time (s).

$$\tau_p = \frac{4\rho_d D}{3C_D\rho_a|\mathbf{U}_i - \mathbf{V}_i|}$$

where ρ_d is liquid density (kg/m^3); ρ_a is air density (kg/m^3); D is droplet diameter (m); and C_D is droplet aerodynamic drag coefficient.

The above control equations maximize retention of droplet spatial force conditions while simplifying droplet motion simulation computation. However, due to the lack of turbulence model support in air velocity simulation, it cannot accurately estimate series parameters such as atmospheric boundary layer velocity fluctuations and turbulent kinetic energy dissipation rates. Therefore, estimation errors in air velocity $\mathbf{U}_i$ are introduced into droplet motion force equations, affecting droplet motion simulation accuracy.

(2) Far-Field Simulation. To reduce computation, AGDISP no longer calculates specific individual droplet movement processes in far-field regions beyond 1000 m, but instead uses Gaussian distribution-based droplet cloud distribution estimation. The spatial distribution of droplet volume fraction is:

$$f(x,y,z) = \frac{Q}{2\pi\sigma_y\sigma_z u}(M_1 + M_2 + M_3)\left\{\exp\left[-\frac{(z-H)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+H)^2}{2\sigma_z^2}\right]\right\}$$

where f is droplet volume fraction; Q is flow rate (m^3/s); x is downwind distance (m); y is crosswind distance (m); z is height (m); H is operation height (m); H_m is atmospheric boundary layer mixing height (m); v is droplet settling velocity (m/s); u is mean wind speed (m/s); σ_y, σ_z are streamwise and vertical standard deviations of droplet clouds; and j is a summation coefficient of 1 and 2.

The above equations introduce atmospheric boundary layer mixing height, incorporating partial effects of atmospheric stability into droplet deposition prediction models, thus providing good practicality while simplifying computation.

(3) Canopy Simulation. Canopy is one of the important influencing factors in plant protection UAV spraying operation simulation. Due to canopy structural complexity and non-uniformity, its simulation is also highly challenging. AGDISP's canopy model employs two-dimensional simplification, ignoring actual canopy structure and using penetration probability of different crop canopy types, droplet path length, and leaf retention efficiency to determine canopy interception rate. The droplet deposition process within the canopy involves first contacting upper leaf surfaces, after which droplets may rebound or shatter into many smaller droplets [**?**]. To address this issue, Schou et al. [**?**] introduced the model invented by Attané et al. [**?**] to describe droplet spreading behavior patterns on leaf surfaces. Assuming spreading droplets form flat cylinders, the control equation is:

$$\frac{d}{dt}(\pi r^2 h) = -\frac{2\pi r h}{\mu}\frac{d\sigma}{dt}$$

where r is cylinder radius (m); t is time (s); θ is contact angle (°); Ohnesorge number $Oh = \frac{\mu}{\sqrt{\rho\sigma D_0}}$; μ is dynamic viscosity coefficient ($\mathrm{N \cdot s/m^2}$); ρ is density ($\mathrm{kg/m^3}$); and D_0 is droplet diameter (m). For droplet leaf impact and fragmentation processes, the critical impact parameter K is introduced:

$$K = Oh \cdot Re^{1.25}$$

where $Re = \frac{\rho D_0 U}{\mu}$. Based on Forster's theory, the critical impact parameter K can be estimated to determine whether droplets will shatter [**?**].

2.1.3 Coupled Model Analysis

Overall, AGDISP, as a globally accepted droplet drift prediction tool, offers fast and stable simulation capabilities, while the inviscid model CHARM significantly reduces computational requirements for droplet movement prediction under complex wind fields. The integrated model theoretically can provide complete time-varying simulation of complex downwash flow fields under UAV operating conditions and real-time droplet movement processes within these airflow fields [**?**, **?**]. The model's advantage lies in its simple computation process and low simulation time consumption, but its droplet motion simulation accuracy is affected by the lack of viscous effects and turbulence models.

In 2018, Teske et al. presented simulation results of droplet movement processes under different crosswind conditions for two different UAV models (DP-12 dual-rotor and ICON octo-rotor) using the CHARM and AGDISP models, marking the availability of a complete inviscid model solution for plant protection UAV spraying process simulation [**?**]. Teske used the CHARM model to simulate UAV wake development, then introduced droplet motion control equations from AGDISP to simulate potential droplet movement processes under wake effects. By analyzing downwash airflow intensity and droplet ground deposition rates under different operating speeds, the concept of critical UAV spraying speed was proposed, revealing that when operating speed exceeds a certain critical value, deposition effectiveness severely declines due to weakened downwash airflow intensity.

However, the integrated CHARM and AGDISP model has only been briefly introduced by Teske et al., with its practical application effects still unclear and far from complete. Based on Teske et al.'s publication, first, AGDISP's wind field simulation component is in a quasi-two-dimensional projection mode and has not yet been integrated with CHARM's three-dimensional wind field. Therefore, the current coupled model can only use CHARM-simulated three-dimensional wind fields with AGDISP's droplet drift model added, resulting in limited simulated droplet drift distance and inability to simulate environmental parameter changes. Second, AGDISP's canopy model cannot be applied to the current coupled model. Finally, the coupled model's joint simulation results for plant protection UAV spraying droplet deposition have not received any experimental verification. Therefore, the inviscid coupled model represented by AGDISP and CHARM requires more field experimental comparison tests and more detailed simulation information disclosure to prove and improve its practicality.

2.2 Computational Fluid Dynamics Models

With rapid development of computer technology, CFD-based numerical simulation methods have become increasingly widespread. CFD methods can select various turbulence models to accurately simulate fluid viscosity and turbulent dissipation processes, thus possessing natural advantages over AGDISP software in simulating complex wind fields. Existing research primarily focuses on wind field distribution and near-field droplet distribution under UAV hover and forward flight conditions, mainly using steady flow average field simulations, including studies on ground and canopy effects on wind fields. However, due to the complex characteristics of rotor wakes, the computational resource consumption is substantial, and existing research has not yet been able to conduct dynamic simulations of the entire droplet drift process.

The main principle of CFD is to obtain spatiotemporal airflow velocity distribution by solving fundamental flow control equations including continuity and momentum conservation equations. The control equations are as follows:

Continuity Equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

Navier-Stokes Momentum Conservation Equation:

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) = -\nabla p + \nabla \cdot \tau + \rho \mathbf{g}$$

where ρ is air density (kg/m^3); $\mathbf{v}$ is mean airflow velocity vector (m/s); p is pressure (N/m^2); τ is viscous stress tensor (N/m^2). Due to turbulence complexity, engineering applications typically use Reynolds-averaged Navier-Stokes (RANS) equations to process Navier-Stokes equations. Reynolds averaging decomposes turbulent instantaneous motion into mean and fluctuating components, modeling the contribution of fluctuating motion to mean motion through Reynolds stress terms and closing the Reynolds-averaged Navier-Stokes equations through turbulence models.

In addition to different flow control equations, droplet motion control equations in CFD models are much more complex than inviscid methods, primarily solved by integrating the Basset-Boussinesq-Ossen (BBO) differential equation for particle forces in Lagrangian coordinates. In Cartesian coordinates, the BBO equation for discrete-phase particles is:

$$m_p \frac{d\mathbf{u}_p}{dt} = m_p \frac{D\mathbf{u}_i}{Dt} - \frac{1}{2}\rho_i V_p \left(\frac{d\mathbf{u}_p}{dt} - \frac{D\mathbf{u}_i}{Dt} \right) - 3\pi\mu d_p f(\mathbf{u}_i - \mathbf{u}_p) - \mathbf{F}_{\text{pressure}} + m_p \mathbf{g}$$

where $V_p \frac{D\mathbf{u}_i}{Dt}$ is the added mass force term; $\frac{1}{2}\rho_i V_p \left(\frac{d\mathbf{u}_p}{dt} - \frac{D\mathbf{u}_i}{Dt} \right)$ is the pressure gradient term; $3\pi\mu d_p f(\mathbf{u}_i - \mathbf{u}_p)$ is the aerodynamic drag term; $\mathbf{u}_i$ is continuous-phase velocity (m/s); $\mathbf{u}_p$ is discrete-phase particle velocity (m/s); μ is fluid dynamic viscosity (kg/(m • s)); ρ_i is fluid density (kg/m^3); ρ_p is discrete-phase particle density (kg/m^3); d_p is particle diameter (m). Droplet-turbulence interactions are simulated through a discrete random walk model, defining each eddy as Gaussian-distributed random velocity fluctuations u', v', w' and time scale τ_e. Velocity fluctuations are defined as $u' = \zeta\sqrt{2k/3}$, and eddy characteristic lifetime as $\tau_e = 0.3k/\varepsilon$, where ζ is a normally distributed random number, k is turbulent kinetic energy, and ε is turbulent dissipation rate.

These equations are generally solved through discretization, including finite volume and finite difference methods.

2.2.1 Finite Volume Method

Since the above flow control equations are nonlinear partial differential equations that cannot be solved exactly, CFD obtains approximate solutions through numerical methods. Currently popular CFD software such as Fluent, CFX, and OpenFOAM are all based on the finite volume method (FVM), which discretizes control equations by converting partial differential equations into algebraic equation sets whose solutions serve as numerical approximations.

Due to FVM's popularity in commercial software, most current UAV wind field simulation results come from this method. However, FVM is greatly affected by mesh quality, and its commonly used upwind scheme has limited accuracy (second-order). Under the same mesh density, simulating rotor tip vortices with FVM more easily produces artificial dissipation than finite difference methods, resulting in tip vortex dissipation rates far exceeding realistic values. In practical applications, this often leads to reduced spatiotemporal accuracy or scale due to insufficient computational resources. As shown in Figure 2 [Figure 2: see original paper], tip vortices generated by low-order schemes dissipate within two periods. Current plant protection UAV wind field simulation results based on commercial software indicate that FVM still cannot fully reproduce rotor tip vortex development processes, and its unsteady flow field simulation accuracy is somewhat constrained.

Current mainstream research directions for plant protection UAV downwash wind field and spraying process simulation are finite volume methods. For example, Yang et al. [**?**, **?**] simulated downwash airflow velocity distribution and droplet spatial distribution of multi-rotor aircraft in hover based on Fluent, combining indoor hover experiments for verification. The simulation used approximately 5.6 million meshes, ignored fuselage effects, and employed the $k-\varepsilon$ turbulence model. The wind field simulation results reflected overall wind field spatial distribution patterns, with simulated average wind speed at marker points showing errors within 9% of experimental measurements and good simulation accuracy, but with significant loss in simulating instantaneous tip vortex fine structures, making it difficult to observe tip vortex evolution processes. Shi et al. [**?**] simulated downwash wind fields and spraying deposition of forward-flight helicopters using 4.78 million meshes and the SST-$k-\omega$ turbulence model, successfully simulating ground deposition distribution of plant protection UAV spraying. The droplet deposition simulation results showed good agreement with field experiments, but wind field development was not examined, making it difficult to determine whether good wind field structure simulation accuracy existed. Zhu et al. [**?**] simulated droplet deposition and drift processes under steady-flow rotor downwash wind fields using 228,000 meshes, then injected particles into the wind field to simulate droplet offset deposition under different crosswind conditions. This simulation did not address unsteady characteristics of rotor downwash airflow or tip vortex evolution issues. Zhang et al. [?] simulated droplet drift processes for N-3 agricultural unmanned helicopters using 1.3 million meshes and surface source spray simulation, with large discrepancies between simulation and experimental results, possibly due to experimental factors. Zhang et al. [?] and Yang et al. [?] simulated rotor downwash airflow effects on spray swath and canopy effects on downwash airflow, using 7.34 million and 5.9 million meshes for cases with and without canopy respectively, with maximum simulation errors around 20% compared to experimental results. Wind field simulation results showed unclear rotor tip vortex structures. The above research primarily focused on simulating plant protection UAV downwash wind fields and near-field droplet deposition, with comparisons to experimental results. Studies involved diverse model structures, surface conditions, and environmental conditions, demonstrating FVM's good robustness and adaptability. However, due to FVM scheme accuracy limitations, analysis of flow field fine structures remains limited, and large-range droplet movement analysis has not yet been addressed.

2.2.2 Finite Difference Method

Unlike FVM, the finite difference method (FDM) discretizes the solution domain into difference grids, replacing continuous solution domains with finite nodes and substituting spatial derivatives at grid points with difference quotients from neighboring nodes, thereby converting differential equations into difference equation sets with grid node parameters as unknowns for solution.

Relative to FVM, FDM's structured grids more easily facilitate construction of high-order precision numerical schemes. High-order schemes such as Weighted Essentially Non-Oscillatory (WENO)/Essentially Non-Oscillatory (ENO) can achieve 4-5 order accuracy. Combined with adaptive mesh technology, FDM enables high spatiotemporal precision simulation of tip vortex evolution, capable of reproducing typical flow structure development processes of real rotor downwash flow fields.

Currently, FDM is mainly applied in basic research fields. For example, Xu and Weng [?] constructed verification models based on different high-order schemes for NACA0012 airfoil single rotors using 1.37 million meshes. Simulation results clearly showed that high-order schemes can retain more rotor tip vortex fine structures under the same mesh conditions and reduce artificial dissipation of tip vortices, maintaining basic morphology over more periods. Lakshminarayan et al. [?] used high-order schemes for detailed simulation of micro coaxial dual-rotor hover wind fields with 6.6 million meshes, focusing on rotor surface flow parameter simulation accuracy and accuracy of tip vortex interaction and evolution process simulation. Kalra [?] used nested grids to refine rotor tip vortex regions, calculating rotor downwash wind field structures with high-precision WENO schemes using 21.6 million meshes. The study found that high-order scheme algorithms could simulate tip vortex structure evolution processes over multiple rotation periods, with flow structures almost completely matching indoor experimental results, though near-ground spanwise velocity profiles still showed approximately 25% error compared to experimental results. The above research possesses higher simulation accuracy than FVM, better simulating rotor tip vortex movement and dissipation processes, but none simulated complex fuselage structures or involved crop canopy and droplet movement process simulation, thus cannot provide direct solutions for plant protection UAV spraying process simulation.

Currently, FDM still faces many challenges in practical application, such as difficulties in constructing structured grids suitable for the algorithm for complex geometries, compatibility issues with two-phase flow algorithms, incomplete canopy modeling methods, excessive computing power requirements for large-space three-dimensional modeling, and is currently only suitable for flow mechanism research under simple geometries and environmental parameters. FDM-based UAV spraying numerical models remain difficult to promote in the short term.

2.3 Lattice Boltzmann Model

In recent years, a computational fluid dynamics method based on the Lattice Boltzmann Method (LBM) has gradually demonstrated advantages in computing three-dimensional flow field problems with complex boundary conditions and non-stationary moving objects [**?**].

2.3.1 LBM Model Principle

LBM is a particle-based method where discrete points in Cartesian coordinates correspond to velocity distributions at lattice nodes. Unlike CFD models based on continuum medium assumptions of Navier-Stokes equations, LBM is based on the Boltzmann equation from molecular kinetic theory, compatible with Navier-Stokes equations at the macroscopic level and possessing broader applicability, primarily through iterative calculations of flow field equilibrium distribution functions and collision operators. A typical three-dimensional 27-degree-of-freedom (D3Q27) LBM is shown in Figure 3 [Figure 3: see original paper] [**?**].

This method is based on particle collision principles, with each discrete unit possessing relatively high degrees of freedom, naturally achieving fourth-order spatial discretization accuracy [**?**], enabling high-precision simulation of rotor tip vortex generation and development processes, with significant simulation accuracy advantages over traditional FVM under the same mesh count. Additionally, the method's parallel computing efficiency is almost unlimited by core count, making it more suitable for parallel computing to improve simulation speed. The D3Q27 discrete velocity model parameters shown in Figure 3 are listed in Table 1 , where sound speed is c_S, discrete velocities are $\mathbf{e}_\alpha$

($\alpha = 0, 1, ..., 26$), weights are w_α, and $c = \delta x/\delta t$, where δx and δt are lattice spatiotemporal steps.

LBM primarily simulates flow field parameter evolution through continuous iteration updates of equilibrium distribution functions. The fluid equilibrium distribution function development equation is:

$$f_i(\mathbf{r} + \mathbf{e}_\alpha \delta t, t + \delta t) = f_i(\mathbf{r}, t) + \mathbf{F}(f_i(\mathbf{r}, t))$$

For the central momentum spatial scattering model, the multiple-relaxation-time LBM model is used, which can independently adjust different relaxation times to control stability, offering higher stability than traditional Bhatnagar-Gross-Krook (BGK) models. Additionally, it overcomes some obvious problems in BGK models, such as inability to change Prandtl numbers and the ratio of dynamic viscosity to second viscosity.

2.3.2 LBM Model Characteristics

Commercial LBM-based software XFlow employs wall-adapting local eddy viscosity models. Due to LBM's limitation by lattice shape, grid sizes near walls are generally larger, requiring specialized turbulence models to improve wall boundary layer calculation accuracy and reduce computation. Since velocity gradient tensors are automatically satisfied locally in LBM, this greatly improves wall large eddy simulation efficiency. For FVM, velocity gradient tensors as spatial derivatives require information from neighboring nodes, making large eddy simulation wall turbulence models in LBM relatively more computationally efficient than in FVM.

LBM possesses unique characteristics advantageous for handling high-precision simulation problems under complex geometries and flow field conditions. Since lattice model structures conform to octree structures, they naturally possess adaptive advantages beneficial for computing complex geometries and flow fields, allowing both encryption of complex surfaces such as rotor surfaces, fuselage, and canopy to improve wall boundary layer simulation accuracy, and dynamic encryption of grid sizes in vorticity-concentrated regions based on vorticity distribution, thereby dynamically improving rotor wake structure identification accuracy. This makes it more suitable for high-precision simulation of plant protection UAV rotor downwash wind fields.

2.3.3 LBM Model Application

In plant protection UAV spraying research, LBM has achieved preliminary application. For example, Zhang et al. [**?**] used LBM to simulate rotor downwash wind field morphological changes under different heights and operating speeds, obtaining spatial distribution evolution of flow field fine structures. Comparison with field wind field measurement results showed the model successfully reproduced wind curtain phenomena measured in field experiments, demonstrating good flow field structure simulation accuracy. Wen et al. [**?**, **?**] used LBM to simulate downwash wind fields of plant protection unmanned helicopters and multi-rotor plant protection UAVs, with tip vortices maintained for about three periods, also showing tail rotor vortex and spiral wake development processes. Simultaneously, droplets with different size distributions based on nozzle measurement results were added to the wind field to simulate near-field distribution under different operating parameters. However, the above research mainly focused on fuselage wake wind fields and droplet spatial distribution within swath width, still lacking detailed comparison with measurement results under the same conditions and far-field droplet movement simulation data.

The author team [**?**, **?**] conducted full-scale three-dimensional space modeling based on actual UAV operating parameters, using the ground as a fixed reference frame to achieve dynamic modeling of downwash wind fields under UAV cruise conditions. Simulation duration exceeded 12 s, with spatial range reaching 80 m (length) × 60 m (width) × 10 m (height).

Figure 4 [Figure 4: see original paper] shows comparisons of plant protection UAV rotor downwash velocity profiles at different spanwise distances based on LBM simulation with field experiments and indoor PIV results. The figure shows that LBM simulation results have relatively large differences from experimental results near ground level, but velocity simulation accuracy is acceptable in regions far from the ground.

Based on obtained flow field motion laws, integrating differential equations for particle forces in Lagrangian coordinates can solve discrete-phase particle motion trajectories to predict droplet deposition patterns. Currently, commercial LBM-based software XFlow has relatively simple droplet motion modeling functions, employing droplet motion equations similar to AGDISP:

$$\frac{d\mathbf{U}_i}{dt} = \mathbf{a}_D(f) + \mathbf{g}_i$$

where $\mathbf{U}_i$ is droplet velocity (m/s); $\mathbf{a}_D(f)$ is acceleration caused by droplet aerodynamic drag (m/s^2); and $\mathbf{g}_i$ is gravitational acceleration (m/s^2). Since Equation (15) lacks a droplet evaporation model, and plant protection UAV spraying processes typically use high-concentration liquids, simulation errors caused by droplet evaporation are relatively smaller than for manned aircraft operations, making this method currently more suitable for UAV spraying simulation.

A set of plant protection UAV spraying spatial distribution scenarios for different operating heights is shown in Figure 5 [Figure 5: see original paper]. The figure demonstrates that LBM can simulate time-accumulated droplet movement processes in three-dimensional large-scale space, obtaining droplet spatial distribution characteristics at different moments under different operating states, with high spatiotemporal resolution. This advantage facilitates rapid simulation and quantitative pattern summarization of droplet deposition and drift characteristics under different operating aircraft types, environmental parameters, and spray conditions, providing strong support for analyzing and optimizing operating parameters and aircraft design. Comparison of plant protection UAV spraying ground deposition distribution results based on LBM simulation with field experimental results is shown in Figure 6 [Figure 6: see original paper]. Results show that differences between model-predicted relative deposition amounts within swath width and field experimental results are within acceptable ranges, indicating credible LBM droplet deposition simulation results.

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3 Numerical Model Verification

The reliability and accuracy of the above inviscid models, computational fluid dynamics models, and lattice Boltzmann model simulation results must be verified through actual measurements of plant protection UAV rotor downwash wind fields and ground deposition distribution of spraying droplets. Current verification methods mainly include field sampling and indoor measurement approaches.

3.1 Field Sampling Methods

Traditional aerial spraying experiments primarily employ field test methods, generally using discrete ground droplet deposition sample detection and spatially discrete wind speed measurement data to evaluate numerical simulation results [?, ?, ?, ?], and obtaining initial spray droplet size distribution information through high-speed wind tunnel tests [?]. However, plant protection UAV rotor downwash airflow is complex, making it difficult for field discrete wind speed measurements to obtain instantaneous flow structures. Additionally, due to proximity to targets, initial spray velocity significantly affects actual droplet deposition, presenting challenges for traditional measurement methods in plant protection UAV spraying process measurement.

For wind field velocity measurement, point-array distributed measurement methods are primarily used to deploy velocity measurement points on a large scale for plant protection UAV rotor downwash wind field measurement. For example, Li et al. [?] used field wireless micro-meteorological wind speed sensor arrays to measure multi-rotor plant protection UAV downwash wind fields, discovering wind curtain effects in actual operations with sudden wind speed changes on both sides of the wind curtain. Wang et al. [?] similarly used field wireless micro-meteorological wind speed sensor arrays to obtain downwash airflow velocity field distributions of three different plant protection UAVs in different directions. Yang et al. [?] used rotating anemometers for point-by-point measurement of multi-rotor plant protection UAV hover state wind field distributions to verify numerical model downwash wind speed simulation accuracy, with experimental measurement results differing from simulation results by less than 10%. The above research used rotating sensors with low cost, suitable for array deployment for large-scale field experiments, but due to rotor rotational inertia, their response frequency to high-frequency airflow direction changes is low, resulting in poor performance when measuring unsteady flow fields such as plant protection UAV rotor downwash airflow, with longer delay times in regions with significant airflow velocity variations, affecting measurement accuracy.

To overcome these issues, other higher-frequency measurement methods have been applied. For example, Zhang et al. [**?**] used hot-wire anemometers for point-by-point measurement of multi-rotor plant protection UAV hover state wind field distributions to verify numerical model simulation accuracy, with measured results differing from numerical simulation results by less than 10%. Hot-wire anemometers possess measurement frequencies above 1 kHz, suitable for instantaneous high-precision measurement of unsteady flow fields. However, due to high cost, array deployment is generally not adopted, with only single-point sampling used to obtain average velocity and pulsation distribution in the overall wind field. Therefore, this scheme is currently mainly used for fixed-height plant protection UAV hover wind field measurement, changing measurement point positions while keeping conditions constant to provide spatial average field measurements.

To address the limitations of the above methods, the author team used three-dimensional ultrasonic anemometer arrays for aerial spraying wind field measurement research [**?**]. Three-dimensional ultrasonic anemometers have measurement frequencies up to 20 Hz, and after spatial array deployment can capture partial high-frequency vortex changes. The author team measured both manned fixed-wing aircraft wake vortex dissipation processes and plant protection UAV downwash airflow fields in hover and cruise operation states, laying foundations for subsequent indoor measurement and numerical simulation of rotor downwash wind fields. Test scenarios are shown in Figure 7 [Figure 7: see original paper].

For droplet deposition distribution measurement, traditional single-point ground sampling methods such as water-sensitive paper or polyethylene cards remain the most mainstream measurement methods for plant protection UAV spraying deposition drift experiments [**?**, **?**]. However, due to the unsteady characteristics of plant protection UAV downwash wind fields, the resulting droplet deposition distribution exhibits non-uniform characteristics, making it difficult for single-point sampling methods with limited spatial resolution to accurately reflect actual conditions. The author team [**?**, **?**] developed a continuous fluorescent paper tape sampler to address these issues, enabling continuous sampling within spray swath width to obtain high spatial resolution droplet deposition distribution results. Its measurement and analysis process is shown in Figure 8 [Figure 8: see original paper].

Additionally, large-range non-contact measurement methods such as infrared thermal imaging, lidar, and near-infrared open-path Fourier transform methods have emerged, increasing the diversity of droplet movement field experimental methods and enhancing intuitive understanding of droplet movement processes. For example, Zhang et al. [**?**] used infrared thermal imagers combined with UAVs to study the effects of unmanned helicopter aerial spray parameters on droplet deposition effects, determining that infrared thermal imaging technology can accurately reflect droplet deposition patterns on rice canopies by measuring crop canopy temperature change rates before and after spraying. Jiao et al. [?] also used infrared thermal imagers to record fixed-wing aircraft spraying droplet cloud movement and deposition processes in space, successfully extracting droplet cloud settlement processes and influence ranges. Gregorio et al. [?] used lidar scanning to obtain data with temporal and spatial resolution, with lidar spray drift measurement values showing determination coefficients above 0.85 compared to horizontal sampling point measurements. Lidar systems can also monitor spray cloud evolution processes and generate two-dimensional images of these clouds. Kira et al. [?] used near-infrared open-path Fourier transform methods to monitor and characterize pesticide droplet drift, finding that after estimating droplet size distribution using water-sensitive paper, the method could obtain droplet loading within scan lines while spectral features could also identify organic phases of pesticide solutions.

However, the above methods still face issues such as high cost, low spatial resolution, interference from complex environmental backgrounds, and difficulty in removing spatial integration effects, and have not yet been widely applied in aerial spraying field experiments compared to traditional sampling methods.

3.2 Indoor Measurement Methods

Due to significant environmental influences in field experiments and large actual operation areas where some refined measurement methods are difficult to implement, indoor measurement methods serve as supplements to field experiments, suitable for obtaining more unsteady flow field validation data to verify different numerical simulation methods' effects on complex rotor wind field simulation. Currently available indoor measurement methods for plant protection UAV downwash wind fields and droplet movement mainly include laser diffraction systems, lidar, laser particle size analyzers, particle image velocimetry (PIV), and phase Doppler interferometry (PDI). Since hot-wire anemometers, lidar and other measurement methods were introduced in field experimental measurement methods, this section focuses on laser particle size analyzers, PIV, and PDI systems.

3.2.1 Laser Diffraction System Laser diffraction systems based on laser diffraction principles can perform particle size detection on various materials and samples, providing detailed particle size distribution data in relatively short time, suitable for indoor spray particle size spectrum measurement work. The instrument utilizes light diffraction phenomena—different particle sizes produce different diffraction angles—to calculate particle size distribution by computing light intensity distribution of different diffraction patterns collected by detectors. Different particle sizes concentrate diffracted light intensity on different detector positions, and particle size distribution is calculated through correlation formulas between particle size and light intensity distribution. Typical instrument systems and measurement principles are shown in Figure 9 [Figure 9: see original paper].

Currently, this instrument has become standard configuration in various spray measurement laboratories, such as USDA-ARS, The University of Queensland, The University of Nebraska, China Agricultural University, and Beijing Research Center for Intelligent Equipment Technology, primarily conducting spray particle size distribution measurement experiments for ground/aerial spraying nozzles [**?**]. The large amount of data obtained and accumulated based on this instrument has also promoted the development of ASABE and ISO standards for ground/aerial spraying nozzle classification. Laser diffraction systems have wide droplet size measurement ranges reaching 0.1-3500 m and scanning frequencies up to 2000 Hz, suitable for rapid scanning detection of high-density spray clouds. However, their function is single, only measuring droplet size spectra, and they can only integrate all droplets along the laser path, unable to obtain three-dimensional spatial distribution of droplet sizes.

3.2.2 PIV System The PIV system primarily studies the development and evolution of plant protection UAV rotor downwash wind fields. The system mainly consists of lasers, high-speed cameras, synchronizers, and particle image velocimetry software, obtaining instantaneous velocity fields through laser planar particle imaging and correlation calculations on particle image time series. A typical instrument system is shown in Figure 10 [Figure 10: see original paper].

Time-resolved PIV technology using high-speed lasers and high-speed complementary metal oxide semiconductor (CMOS) cameras is currently the only mechanistic research method capable of obtaining instantaneous flow structures of UAV downwash wind fields. In UAV downwash wind field measurement, it can provide high spatiotemporal resolution flow field information, enabling accurate measurement of the entire process of tip vortex movement and dissipation to evaluate model simulation accuracy for tip vortices.

Currently leading research institutions in this field include the German Aerospace Center (DLR), University of Maryland, and National University of Singapore. Among them, Raffel at German DLR is a major contributor to PIV technology development, leading the European helicopter experimental testing project. His team used PIV technology for detailed measurement of rotor surfaces and fuselage-near flow fields, primarily for analyzing rotor surface efficiency and forces under different flow states, with less involvement in rotor downwash airflow and surrounding airflow research [**?**]. The Leishman team at the University of Maryland has years of research experience in rotor wind field measurement, comprehensively using numerical simulation, flow visualization, and high-speed PIV measurement technologies to conduct in-depth research on single-rotor downwash wind field fine structure development patterns. However, limited by indoor experimental conditions, their research focuses on micro-rotor studies, with methods that can be referenced but results difficult to directly replicate for plant protection UAV operations [**?**]. Nathan at the National University of Singapore used moving walls and high-speed PIV technology to study wind field evolution processes of rotors at different forward flight speeds, considering the effects of relative motion between rotors and ground on downwash airflow structure evolution under forward flight states, but still limited by indoor experimental model scale constraints [**?**]. The above researchers have conducted extensive basic research on unsteady rotating flow field measurement for UAVs, but due to indoor experimental condition limitations, have not yet involved large-range flow field measurement research including UAV fuselage.

In response to the above situation, the author team pioneered indoor scaled-model PIV instantaneous flow field measurement research for plant protection UAVs such as AF25B and DJI MG1P, obtaining large amounts of data on rotor tip vortex development and dissipation processes, typical vortex structures, average velocity fields, and streamlines. These results were compared with the team's previous field operation wind field test results and developed numerical simulation results for this UAV type, building a bridge from field experiments to numerical simulation [**?**, **?**].

3.2.3 PDI System While PIV systems primarily study plant protection UAV rotor downwash wind field development and evolution, the PDI system mainly studies the initial movement process of plant protection UAV spraying liquids. Since plant protection UAV spraying processes occur close to the canopy, initial spray droplet velocity distribution significantly affects deposition distribution. Traditional laser diffraction systems used for droplet size measurement cannot meet requirements for velocity distribution measurement.

The PDI system uses a diode-pumped solid-state laser to form an optical system, employing laser phase Doppler effects to simultaneously measure droplet size and velocity passing through the laser focal point. Its size measurement range is 0.3-7000 m, velocity measurement range is 300 m/s. The phase Doppler interferometry system is shown in Figure 12 [Figure 12: see original paper].

This method can be applied to spray particle size and velocity distribution measurement for various nozzle types. For example, Nuyttens et al. [**?**, **?**] conducted detailed measurements of particle size and velocity distributions for different nozzle types, analyzing their potential effects on droplet deposition and drift. Li et al. [**?**] conducted statistics on particle size and velocity distributions at different heights for flat fan nozzles under low pressure, obtaining droplet size fitting equations based on spray angle, flow rate, and orifice diameter. Existing research has not yet investigated droplet size and velocity distribution variation patterns under complex wind field effects, and initial velocity distribution measurement results have not been applied as reference conditions in numerical models.

The author team [?] addressed the above research status by measuring initial droplet size and velocity distributions generated by commonly used flat fan nozzles for plant protection UAVs based on PDI test platforms, combined with numerical models to analyze their spatial distribution changes under rotor wind field effects, providing initial spray parameter support for droplet movement deposition and drift prediction.

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4 Comprehensive Analysis

Currently, inviscid models, computational fluid dynamics models (FVM and FDM), and lattice Boltzmann models have all been applied in simulating plant protection UAV spraying processes, each possessing distinct advantages, disadvantages, and applicable scopes. A comparison of applicability, complexity, and other pros and cons of each model is presented in Table 2 .

Table 2 Comparison of advantages and disadvantages of numerical models for plant protection UAV spraying

Model Type	Advantages	Disadvantages
Inviscid Model	Low computational resource consumption; good accuracy for near-field tip vortex development; extensive validation for manned aircraft far-field drift; applicable to complex conditions	Tip vortex non-dissipative characteristics unrealistic in far-field; cannot handle large-space range simulation; 3D wind field and 2D drift model integration still problematic; simplified canopy model incompatible
Finite Volume Method	Complete theoretical foundation; wide applicability; strong extensibility; mainstream commercial software	Low scheme accuracy causes artificial dissipation; high computational cost for large 3D simulations; tip vortex dissipation too fast
Finite Difference Method	High-order accuracy (4-5 order); good for fine vortex structure simulation; low artificial dissipation	Difficult structured grid generation for complex geometries; high computing power requirements; limited to basic research currently

Model Type	Advantages	Disadvantages
Lattice Boltzmann Method	4th-order accuracy; automatic mesh adaptation; good for complex geometries; high parallel efficiency	Cubic lattice causes grid number explosion near walls; simple droplet models; no evaporation model yet

Inviscid models for plant protection UAV spraying simulation offer low computational resource consumption, good simulation accuracy for near-range tip vortex development, extensive validation for manned aircraft far-field droplet drift simulation, and applicability to complex conditions. The main challenges include the non-dissipative characteristics of tip vortex structures in the vortex element method being unrealistic in far-field conditions, currently unable to handle large-space range simulation problems. Additionally, the combination of three-dimensional simulation in the vortex element method and two-dimensional far-field droplet drift models still has interface difficulties, with no literature validating their combined effects. The simplified canopy model in two-dimensional droplet drift models also cannot be applied to three-dimensional vortex element method models, further constraining inviscid models' capability to simulate plant protection UAV operations under actual conditions including canopy effects.

In computational fluid dynamics models, the finite volume method has a complete theoretical foundation, wide applicability, and strong extensibility, making it the preferred method for mainstream commercial software and suitable for simulating wind field changes and droplet far-field drift effects caused by plant protection UAV operations under complex meteorological and terrain conditions. The main challenges include low scheme accuracy causing artificial dissipation, high computational cost for large three-dimensional simulations, and tip vortex dissipation rates being too fast. With support from adaptive mesh and parallel algorithms, issues of high artificial dissipation rate and computational overhead can be somewhat alleviated. In the future, it will remain the best method for simulating plant protection UAV wind fields and droplet movement processes under complex meteorological and operating conditions to obtain accurate results. This method is suitable for mechanistic and basic research on aerodynamic characteristics and wind field distribution changes caused by minor structural adjustments to UAV models and airfoils. Relying on droplet evaporation, complex turbulence, and various user-defined functions, this method is also suitable for simulating wind field changes and droplet far-field drift effects under complex meteorological and terrain conditions. The finite difference method will continue to leverage its simulation accuracy advantages in basic research fields, conducting refined simulations of wake vortex structures generated by specific aircraft models, complementing indoor experimental results, and providing more accurate wake vortex movement and dissipation process comparisons for other numerical models to help verify and improve simulation accuracy of other models.

The lattice Boltzmann method-based numerical model plays an irreplaceable role in plant protection UAV operation wind field simulation, droplet movement and drift process simulation, application parameter optimization, and nozzle selection, being suitable for rapid simulation of wind field distribution and droplet movement under complex-geometry plant protection UAVs and canopy interactions. Future development needs for this model include further optimization of its wall turbulence model to overcome simulation accuracy losses caused by coarse grids near walls, balancing computational cost and accuracy, while strengthening droplet evaporation, collision, fragmentation models, and environmental temperature-humidity models.

Regarding numerical model verification methods, both field experiments (ultrasonic/cup anemometers, water-sensitive paper and polyethylene cards, fluorescent paper tape, non-contact measurement methods) and indoor experiments (PIV, PDI) have been applied in verifying plant protection UAV spraying numerical model simulation accuracy, each with distinct advantages, disadvantages, and applicable scopes. A comparison of pros and cons of each method is presented in Table 3 .

Table 3 Comparison of advantages and disadvantages of verification methods for numerical models

Verification Method	Droplet Velocity/Position	Time Resolution	Spatial Resolution	Field Adaptability
Ultrasonic Anemometer	Wind speed only	High (20 Hz)	Low (point)	Good
Cup Anemometer	Wind speed only	Very low	Medium (array)	Excellent
Water-sensitive Paper	Deposition only	N/A	Low (discrete)	Good
Hot-wire Anemometer	Wind speed only	Very high (>1 kHz)	Low (point)	Poor
Infrared Thermal Imaging	Droplet cloud position	Medium	Medium	Medium
PIV	Velocity field	High	High (2D plane)	Poor (mainly indoor)
PDI	Velocity & size	High	Medium (point)	Medium

Ultrasonic and cup anemometers are the most important means for measuring plant protection UAV field operation wind fields, usable for verifying numerical simulation wind field velocity accuracy. Ultrasonic anemometers have high measurement frequency but are expensive, bulky, and single-point, limiting popularization. Cup anemometers are small, low-cost, and suitable for large-scale array deployment, but have very low response frequency and cannot handle large wind field fluctuations. Water-sensitive paper, polyethylene cards, and fluorescent paper tape are mainly used for measuring liquid deposition distribution within plant protection UAV spray swath width for verifying numerical model predictions of droplet ground deposition distribution. Water-sensitive paper and polyethylene cards use discrete sampling layouts with spatial resolution limited by point density, making it difficult to truly reflect highly non-uniform droplet deposition caused by unsteady flow fields. Fluorescent paper tape continuous sampling compensates for this deficiency, greatly improving droplet deposition sampling spatial resolution and showing good application prospects.

Large-range non-contact measurement methods such as infrared thermal imaging, lidar, and near-infrared open-path Fourier transform methods can provide measurement results with temporal and spatial resolution without interfering with measured objects, enhancing intuitive understanding of droplet movement processes. However, these methods still face issues of high cost, low spatial resolution, environmental background interference, and difficulty in removing spatial integration effects, and have not been widely applied in aerial spraying field experiments compared to traditional sampling methods.

Laser diffraction systems are standard configuration in spray measurement laboratories, offering simple and fast measurement advantages. However, their function is single, only measuring droplet size spectra, and they can only integrate all droplets along the laser path, unable to obtain three-dimensional spatial distribution of droplet sizes. Indoor experiments, in addition to traditional laser diffraction measurement methods, will be based on high-frequency measurement methods such as PIV and PDI. On one hand, they will continue to improve system automation and intelligence levels, reduce operation difficulty and layout requirements, and enhance indoor measurement efficiency. On the other hand, they will continue to expand application scope, such as actively developing large-range outdoor PIV wind field and droplet measurement technology, portable PDI spray real-time measurement systems, etc., to achieve natural connection between indoor and outdoor measurement results and provide more comprehensive verification information support for numerical modeling.

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5 Outlook

With continuous research advancement, various simulation methods for plant protection UAV spraying droplet deposition and drift will continue to be improved and optimized. The three simulation methods mentioned above will adapt to different research needs based on their characteristics. For example, general engineering applications requiring fast computation will still primarily use inviscid models; research involving flow detail analysis and spraying optimization will increasingly adopt the lattice Boltzmann method; for complex meteorological conditions, basic flow structures, and two-phase flow research, computational fluid dynamics models remain the best choice.

In inviscid models, the interface between near-field three-dimensional simulation and two-dimensional far-field droplet drift simulation will continue to be optimized to eventually form a unified fast simulation solution for plant protection UAVs, while further leveraging this method's computational speed advantage to evolve toward real-time simulation of spraying droplet deposition and drift based on actual UAV flight measurement data. This model may become a standard configuration for plant protection UAV operation ground stations, capable of real-time prediction of potential droplet drift zones during plant protection UAV spraying operations based on operation and environmental parameters, thereby enabling targeted route replanning or operational setting changes.

In computational fluid dynamics models, the finite volume method, with support from adaptive mesh and parallel algorithms, can alleviate problems of high artificial dissipation rate and computational overhead. In the future, it will remain the best method for simulating plant protection UAV wind fields and droplet movement processes under complex meteorological and operating conditions to obtain accurate results. This method is suitable for mechanistic and basic research on aerodynamic characteristics and wind field distribution changes caused by minor structural adjustments to UAV models and airfoils. Relying on droplet evaporation, complex turbulence, and various user-defined functions, this method is also suitable for simulating wind field changes and droplet far-field drift effects under complex meteorological and terrain conditions. The finite difference method will continue to leverage its simulation accuracy advantages in basic research fields, conducting refined simulations of wake vortex structures generated by specific aircraft models, complementing indoor experimental results, and providing more accurate wake vortex movement and dissipation process comparisons for other numerical models to help verify and improve simulation accuracy of other models.

The lattice Boltzmann method-based numerical model plays an irreplaceable role in plant protection UAV operation wind field simulation, droplet movement and drift process simulation, application parameter optimization, and nozzle selection, being suitable for rapid simulation of wind field distribution and droplet movement under complex-geometry plant protection UAVs and canopy interactions. This model will need further optimization of its wall turbulence model to overcome simulation accuracy losses caused by coarse grids near walls, balancing computational cost and accuracy. Simultaneously, it needs to strengthen droplet evaporation, collision, fragmentation models, and environmental temperature-humidity models.

Regarding numerical model verification methods, field experiments will continue to maintain their characteristics while addressing issues of high environmental influence and low spatiotemporal resolution, mainly including: (1) Developing inexpensive, miniaturized three-dimensional ultrasonic and hot-wire anemometers with high temporal resolution for wind field measurement, reducing measurement point intervals and increasing point numbers to compensate for insufficient spatial resolution; (2) Developing automated fluorescent paper tape detection and other continuous sampling methods for droplet deposition detection to improve spatial resolution; (3) Deploying high-frequency wind field measurement equipment for environmental background to simultaneously subtract background noise and offset random effects caused by environmental wind field changes on measurement results; (4) Developing non-contact measurement methods for droplet movement/position determination, such as infrared thermal imaging, lidar, and near-infrared open-path Fourier methods, focusing on improving their spatiotemporal resolution and anti-environmental background interference capabilities.

In addition to traditional laser diffraction measurement methods, indoor experiments will be based on high-frequency measurement methods such as PIV and PDI. On one hand, they will continue to improve system automation and intelligence levels, reduce operation difficulty and layout requirements, and enhance indoor measurement efficiency. On the other hand, they will continue to expand application scope, such as actively developing large-range outdoor PIV wind field and droplet measurement technology, portable PDI spray real-time measurement systems, etc., to achieve natural connection between indoor and outdoor measurement results and provide more comprehensive verification information support for numerical modeling.

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Research Progress of Key Technologies and Verification Methods of Numerical Modeling for Plant Protection Unmanned Aerial Vehicle Application

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Abstract: With the increasing application of plant protection unmanned aerial vehicle (UAV) in precision agriculture, the numerical simulation methods for the development of the downwash flow field of the plant protection UAV and the deposition and drift process of droplets affected by the downwash flow field have achieved rapid and diversified development, but the advantages, disadvantages, scope of application, and verification of each method still lack a systematic review. This article discusses the inviscid model, computational fluid dynamics model and lattice Boltzmann model (LBM) respectively. The advantage of the inviscid wake vortex model based on the vortex element method is that the calculation process is simple. Moreover, integrated with the most widely used aerial spray drift prediction software AGricultural DISPersal (AGDISP), it can be a promising way to do real-time UAV spray drift prediction. But due to lack of viscosity and turbulence models, the droplet deposition and drift simulation accuracy of inviscid model is relatively lower than other models. The computational fluid dynamics (CFD) model includes the finite volume method (FVM) and the finite difference method (FDM). The FVM in the computational fluid dynamics model has high robustness and can be applied to the simulation of various complex environments. Many commercial CFD software are based on FVM and achieved a fast development in aerial spray modeling recently. However, the FVM is greatly affected by the quality of the mesh, and its commonly used upwind style has limited accuracy (second-order accuracy). Under the same mesh density, it is easier to generate artificial dissipation when simulating the rotor tip vortex than the finite difference method. As a result, the simulated rotor tip vortex dissipation speed is much faster than the actual situation. Compared with the FVM, the structured grid used in the FDM is easier to construct a high-order precision numerical format. Which can reach 4-5 orders of accuracy, and with adaptive grid technology, FDM can simulate the evolution of rotor tip vortex with high temporal and spatial accuracy, and can reproduce the typical flow structure development process of the real rotor downwash flow field. However, it also has problems such as high grid structure requirements and excessive computing power requirements. LBM has advantages in computing three-dimensional flow field problems with complex boundary conditions and non-stationary moving objects. However, there are still shortcomings in its functional diversity and completeness. The accuracy of the numerical models mentioned above still needs field test and indoor experiment such as high-speed Particle Image Velocimetry (PIV)/ Phase Doppler Interferometry (PDI) method to verify and optimize. The authors finally pointed out the future direction of plant protection UAV application simulation and verification.

Key words: plant protection UAV; downwash flow field; numerical simulation; droplet deposition and drift; computational fluid dynamics