

Article

Study on the Characteristics of Downwash Field Range and Consistency of Spray Deposition of Agricultural UAVs

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Abstract: Agricultural unmanned aerial vehicles (UAVs), increasingly integral to crop protection through spraying operations, are significantly influenced by their downwash fields, which in turn affect the distribution of spray droplets. The key parameters impacting spray deposition patterns are the velocity of the downwash airflow and its spatial extent. Understanding the interplay of these parameters can enhance the efficacy of UAV applications in agriculture. Previous research has predominantly focused on downwash airflow velocity, often neglecting the spatial scope of the downwash. This paper presents an applied foundational study grounded in the compressible Reynolds-averaged Navier–Stokes (RANS) equations. Leveraging a dependable $k-\epsilon$ turbulence model and dynamic mesh technology, it develops an effective three-dimensional computational fluid dynamics (CFD) approach to analyze the downwash field’s distribution characteristics during UAV hover. To validate the CFD method, a visualization test was conducted using EPS (expanded polystyrene foam) balls dispersed in the airspace beneath the UAV, illustrating the airflow’s spatial distribution. Additionally, a parameter η was introduced to quantify changes in the wind field’s range, enabling the mapping of the cross-sectional area of the downwash airflow at various velocities within the UAV’s airspace. The study reveals that the downwash field’s overall shape evolves from a “four-point type” to a “square-like” and then to an “ellipse-like” configuration. Lower downwash airflow velocities exhibit a more rapid expansion of the wind field area. High-velocity downwash areas are concentrated beneath each rotor, while lower-velocity zones coalesce under each rotor and extend downward, forming a continuous expanse. Within the UAV’s downwash area, the deposition of droplets is more pronounced. At a given nozzle position, an increase in downwash airflow velocity correlates with greater droplet deposition within the downwash field. This research bridges a gap in downwash field studies, offering a solid theoretical foundation for the development of future UAV downwash field models.

Keywords: quadrotor agricultural UAV; downwash field area; CFD simulation; wind visualization



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1. Introduction

At present, to solve the shortcomings of traditional plant protection operations, such as high labor intensity, low efficiency, high time consumption, and poor flexibility, a variety of automated machinery for plant protection operations is instead used in China. Among automated approaches, the use of agricultural unmanned aerial vehicles (UAVs) reflects the advantages of high efficiency, low cost, and good effect during spraying operations [1], and UAVs have gradually become a major plant protection machinery. Studies have shown that the downwash field of various rotorcraft has a major impact on the deposition distribution characteristics of spray droplets [2,3]. In the field of UAV sowing, the downwash field also affects the movement trajectory of seeds in the air and affects the seeding effect [4,5].

In low-altitude operations, a UAV's downwash field will change the shape of crops and affect their yield [6]. In terms of gas monitoring by UAVs, the downwash field of UAVs will affect the accuracy of monitoring data [7]. It is of high value to study the basic laws of the UAV downwash field. Fan et al. (2022) studied a method of acquiring images of the effects of airflow on the spray target by video aerial photography and computer vision to process the images and obtain the characteristic information in rice fields. The UAV downwash field disturbance to the area of the crop canopy is known as the "wind vortex". The regularity of different "wind vortex" parameters under different UAV flight parameters was summarized [8]. Liu et al. (2022) established the correspondence between UAV flight parameters and the "wind vortex" so that the UAVs can control the parameters of the "wind vortex" during operation [9].

2. Related Works

The traditional research method for examining the downwash field of UAVs is to reconstruct and analyze the downwash field of UAVs by using the method of experimental measurement and multi-point traversal. Li et al. (2014, 2015) tested the distribution characteristics of the downwash field of an eight-axis UAV under flight conditions by using a tri-directional linear array downwash airflow velocity sensor and obtained the peak downwash airflow velocity in three directions: parallel to the UAV's flight direction (X), perpendicular to the flight direction (Y), and perpendicular to the ground (Z), as well as downwash airflow velocity characteristics in the corresponding wind direction [10,11]. Lan et al. (2021) used a three-phase downwash airflow velocity sensor to study the distribution characteristics of the downwash field of the DJI T16 plant protection UAV and the influence of the wind field on spray depositions. The results showed that the wind field parallel to the UAV flight direction (X) and vertical to the ground (Z) tended to weaken with increasing flight height. The downwash field perpendicular to the flight direction (Y) showed a stronger trend, the downwash fields perpendicular to the flight direction (Y) and vertical to the ground (Z) had a significant impact on spray deposition, and the optimal flight height of the DJI T16 plant protection UAV was 2 m [12]. Zhan et al. (2022) used a three-phase downwash airflow velocity sensor to measure the downwash airfield of a four-axis UAV P20 working in the field and studied the influence of the wind field on the penetration and deposition of spray droplets. The results showed that the downwash field was conducive to spray deposition and penetration, which could improve the uniformity of droplet distribution and reduce drift [13]. Yang et al. (2022b) used downwash airflow velocity sensors to study the downwash airflow velocity characteristics of the downwash field of a six-rotor UAV in a mature corn field, and the results showed that the corn canopy affected the uniformity, movement, and intensity of the downwash field [14]. Although the experimental test method can intuitively obtain data on the downwash field of a UAV, it has some disadvantages, such as the large number of experiments required and high reliability on only a single UAV and a single experimental environment. At the same time, the experimental measurements indicate a high dependence on sensors, which introduces two problems. These problems can be analyzed by taking downwash airflow velocity sensors as an example. The first issue is that it is difficult to find a suitable downwash airflow velocity sensor. The small downwash airflow velocity sensor on the market can only measure the downwash airflow velocity in one wind direction, which is not suitable for measuring turbulent downwash airflow velocity. The sensor that can measure the downwash airflow velocity of multiple wind directions has a large size and is thus not suitable for measuring single-point downwash airflow velocity. Second, the calibration of different downwash airflow velocity sensors is different, and the downwash airflow velocity value obtained by different sensors when measuring the same point is different, which brings systematic errors to the experimental measurement method.

With the rapid development of computer technology in the last century, computational fluid dynamics (CFD) has become a powerful tool to study the physical properties of fluids and to solve and analyze engineering problems. Compared with the experimental test

method used to study the nature of the downwash field of UAVs, CFD technology can simulate the movement of fluids to not only supplement some data that are difficult to obtain in the experiment but also more effectively analyze and compare the downwash fields of different UAVs [15]. In addition, CFD reduces the dependence on sensors, thereby reducing the system error caused by the sensors.

Two CFD methods can be used to calculate the downwash field of a UAV. One method is the simulation calculation based on the Euler continuity equation, which is more mainstream now [16], and the other method is the novel LBM algorithm [17]. In the simulation calculation based on Euler's continuity equation, turbulence caused by airflow interaction needs to be considered [18]. The predecessors summarized the Reynolds mean Navier–Stokes (RANS) model from the Navier–Stokes (N–S) equation combined with experimental experience to solve turbulence. This method becomes a more effective and feasible means of solving engineering problems. Coombes et al. (2022) used the RANS equation to simulate the static and moving states of a single rotor and multi-rotor and studied the distribution characteristics of droplets under the rotors. The results showed that in the static state, the peak value of the droplet distribution decreased with increasing rotor height and increased with increasing rotor speed. During movement, there was a critical speed; when the rotor moving speed exceeded this speed, the droplets below the rotor did not reach the ground [19]. However, the RANS equation still cannot be used to calculate the Reynolds stress in turbulence, so it is necessary to establish a turbulence model to perform such calculations. Based on the RANS model and the combination of theoretical and experimental experience, a series of model assumptions is introduced. The commonly used turbulence models are the k - Ω model (standard, SST) and k - ϵ model (standard, RNG, realizable k - ϵ). Zheng et al. (2018) simulated the downwash field of the JF01-10 six-rotor plant protection UAV with the SST k - Ω turbulence model and studied the characteristics of the downwash field of the UAV. The results showed that with an increasing hovering height, the minimum flow velocity of the downwash field of the UAV first increased and then decreased, and the surrounding pressure and ground effect decreased. Turbulence was more stable and conducive to flight control [20]. By using the SST k - Ω turbulence model, Guo et al. (2020) simulated the downwash field when a four-rotor agricultural UAV hovered and studied the distribution characteristics of the downwash field in the space-time dimension. The results showed that most areas of the downwash field were stable within 4.5 s, and the vertical downwash airflow velocity direction was the main part of the downwash field. The downwash field showed an obvious “contraction and expansion” phenomenon [21]. The k - Ω model has higher accuracy, but compared with the k - ϵ model, its efficiency is lower, and convergence is more difficult to achieve. Thus, the k - ϵ model is more widely used. Based on the RANS equation and the RNG k - ϵ turbulence model, Hao et al. (2019) simulated the downwash wind field of a six-rotor plant protection UAV. At the same time, the porous model was used to simulate the plant canopy, and the interaction characteristics between the UAV wind field and the plant canopy were studied. The results showed that without the obstruction of the plant canopy, the downwash field of the UAV developed downward in a “cylindrical shape”, and the downwash airflow velocity stability zone appeared at 0.6–1.7 m from the UAV. When plant canopy blocking occurred, the downwash airflow velocity stability zone no longer appeared in the UAV downwash field [22]. At the same time, it was found that the air speed in the plant canopy was comprehensively affected by the height of five factors [23]. Yang et al. (2017) analyzed the dynamic development law and distribution characteristics of the downwash wind field of an SLK-5 six-rotor agricultural UAV by combining the RNG k - ϵ turbulence model. Research showed that the maximum speed of the downwash airfield was close to 10 m/s, and the downwash airflow velocity direction of the vertical ground (Z) was the main body of the wind field [24]. Wang et al. (2021) combined the RNG k - ϵ turbulence model to simulate and calculate the six-rotor UAV with different inclination angles to study the influence of the rotor inclination angle on the downwash field of the UAV. The results showed that with the change in the inclination angle from 8° to 0°, the downwash wind field of the

UAV tended to tilt and contract toward the central axis. The linear attenuation range of the airflow velocity also decreased [25]. Among the k - ϵ models, the calculation accuracy of the realizable k - ϵ turbulence model is the highest [26]. Ma et al. (2022) combined the realizable k - ϵ model to simulate the flow field around a quadrotor UAV and studied the influence of the flow field around the UAV on gas sampling. The results showed that the airflow intensity above the rotor of the UAV was smaller than that below the rotor. Combined with the realizable k - ϵ model, Fan et al. (2019) explored the influence of the wheelbase of a quadrotor UAV on its downwash field. The results showed that in the hovering state when the rotor pitch-to-diameter ratio was from 1.1 to 1.4, the higher the pitch-to-diameter ratio was, the lower the airflow aggregation degree was [27]. Combined with the realizable k - ϵ model, Yang et al. (2017) studied the characteristics of the downwash field of a six-rotor UAV. The results showed that the longitudinal section of the downwash air presented the phenomenon of “contraction-expanding-recontraction”, and the cross section showed the airflow “entering” and “exporting” zones due to the interference between the rotors [3]. The authors used the same method to study the influence of pesticide loads on the downwash field distribution of UAVs. The results showed that the larger the load, the higher the downwash airflow velocity in the downwash field and the more obvious the interference phenomenon between rotors. Under different loads, the longitudinal section of the wind field showed different states [28]. For a comprehensive comparison, the RANS equation of the realizable k - ϵ model is used in this paper for simulation calculation research.

In previous studies, the discussion regarding the factors affecting the distribution of sprayed droplets has focused on the downwash airflow velocity of the downwash field under the UAV. Several studies have mentioned the discussion of the maximum velocity distribution of the washing field under different UAVs. However, the distribution of spraying droplets is affected not only by the airflow velocity in the wind field but also by the range of the downwash field of the UAV [29,30]. Only discussing the distribution of the downwash airflow velocity in the downwash field is not sufficient to determine the overall influence of the wind field on the spraying operation. Therefore, it is necessary to supplement the discussion of the scope of the downwash field (Table 1).

Table 1. Comparison of this study with other studies.

	Other Research	This Paper
Research object	Downwash airflow velocity ([1,10,11]) focused on the characteristics of downwash airflow velocity. Ref. [3] analyzed the wind distribution characteristics of the downwash field based on its velocity. Ref. [21] studied the distribution characteristics of the downwash field in the space-time dimension.)	Downwash airflow velocity and downwash range
Research method	Experimental measurement or simulation ([1,10,11,13], etc., used anemometers in the field to study the downwash of UAVs [20–22] etc., utilized simulation calculations to study the downwash of UAVs.)	Experimental measurement and simulation

3. Materials and Methods

In summary, as shown in Figure 1, this paper validates the accuracy of simulation calculations through the design of relevant experiments and ultimately discusses the distribution characteristics of downwash airflow velocity and wind field ranges in the space below the UAV using simulation data. The RANS equation, when paired with the realizable k - ϵ turbulence model, facilitates the simulation of downwash airflow velocity distribution within the downwash field of the DJI450 (Appendix A). This small unmanned aerial vehicle (UAV), manufactured by DJI, is frequently utilized in precision agriculture for

remote sensing tasks and the application of low-weight pesticides [31,32]. The following range of the downwash field is the verification standard to verify the correctness of the simulation results. The simulation results are used to discuss the wind field range and downwash airflow velocity distribution law of each downwash airflow velocity in the DJIF450 downwash field at different heights from the UAV. Finally, the relationship between the wind field range of the UAV and the deposition of droplets is explored through the actual spraying experiment.

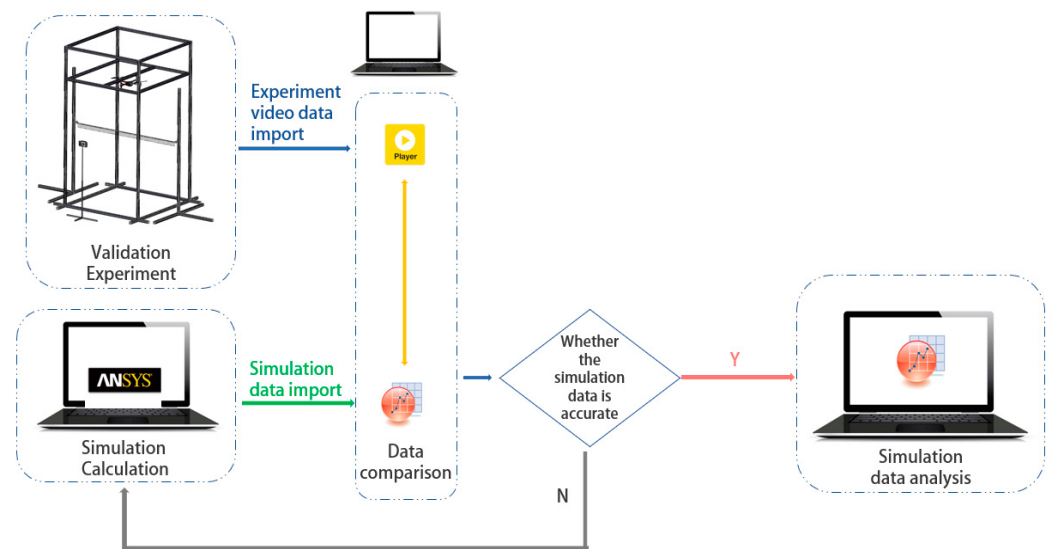


Figure 1. Research methods.

The research target of this paper is the DJIF450 UAV. Because the DJIF450 UAV and some large plant protection UAVs are 4-axis-structure UAVs, the difference is only in the size of the arm. The DJIF450 parameters are shown in Table 2. In this case, X-distribution refers to a classification of UAVs in terms of flight control, meaning that the forward direction of the UAV is between two rotors. Imitation APC rotor refers to a rotor that has the same shape as an APC rotor but is made of slightly different materials. The parameters of the Quansheng 2216 motor are shown in Table 3.

3.1. Simulation Calculation

It is necessary to establish the corresponding simulation model to calculate the UAV downwash field. The establishment of the simulation model is divided into three steps: (1) the 3D model of DJIF450 is developed; (2) the 3D model is meshed; and (3) the simulation parameters are set.

3.1.1. Establishing the 3D Model of the DJIF450

The most important part of the UAV 3D model is the rotor model. In this paper, a T7+ handheld scanner (Appendix A) is used to scan the rotor to develop the rotor model. The scanned rotor model is shown in Figure 2 with a scanning accuracy of 0.2 mm, and the obtained rotor model is used to establish the 3D model of the DJIF450. The rotor is 10×4.7 p, which means that the rotor is 10 inches long and the pitch of the rotor is 4.7 p.



Figure 2. The 3D model of the UAV rotor.

To eliminate the occlusion effect of the UAV rack on the UAV rotor airflow, all four rotors are installed below the rack, as shown in Figure 3. At the same time, to facilitate the following explanation, a Cartesian coordinate system is established at the center of the plane where the four rotors are located, in which the rotor rotating counterclockwise in the positive half-axis of the X-axis is the No. 1 rotor, and the rotor rotating clockwise in the positive half-axis of the X-axis is the No. 3 rotor. Accordingly, rotor No. 2 rotates counterclockwise and rotor No. 4 rotates clockwise. The positive half-axis of the Y-axis points above the UAV.

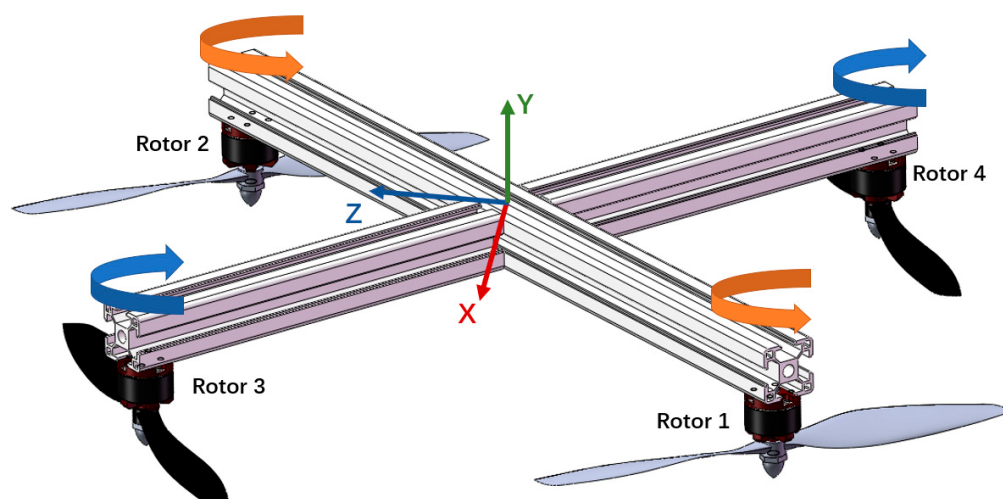


Figure 3. UAV layout and coordinate system.

To reduce the computational cost in the simulation calculation, it is necessary to use SOLIDWORKS 2018 to reasonably simplify the 3D model of the DJIF450 on the premise of ensuring calculation accuracy. In a previous study [3], the frame, motor, and other accessories were removed; moreover, only the wheelbase and distribution mode between the rotors were left, and they had little effect on the results of the simulation calculation, as shown in Figure 4.

Table 2. Parameters of the DJIF450.

Name	Model (Size)
Mode of distribution	“X” distribution
Wheelbase	450 mm (shown in Figure 4)
Rotor	Imitation APC 10 × 4.7 p (HY, China)
ESC (electronic speed controller)	HOBBYWING, China (X-Rotor 20 A)
Rotor specification	Quansheng 2216 KV950 (Table 3)

Table 3. Parameters of the Quansheng 2216 KV950.

Parameters	Value
Manufacturer	Quansheng (China)
Maximum current	15 A
Size	φ22.7 mm × H (height) 24.2 mm
Mass	52 g
Maximum power	280 w

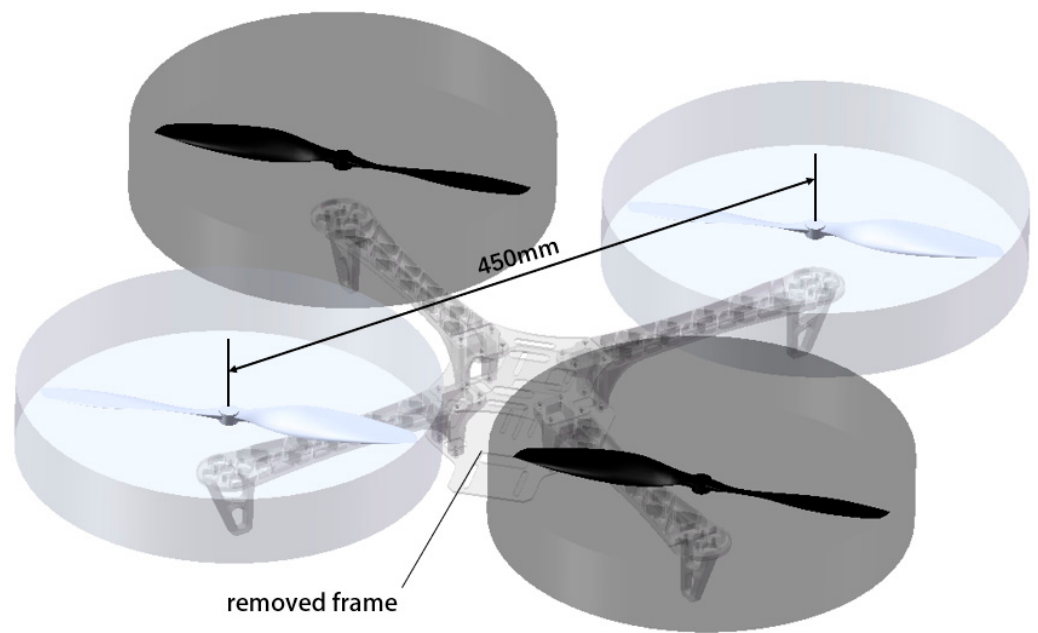


Figure 4. Simplified model of the DJIF450 (the 450 mm label refers to the wheelbase).

3.1.2. Meshing the 3D Model

This paper utilizes the Ansys 2022R1 version. The simplified 3D model of the UAV is meshed to establish the simulation model, as shown in Figure 5. The simulation model of the UAV established based on the 3D model of the DJIF450 UAV is divided into an external static domain containing four internal dynamic domains, namely, an external environmental static domain and four rotating rotor dynamic domains. Since the actual test environment has a restricted height of 3 m, the four dynamic domains are placed 2 m away from the bottom surface of the boundary domain. Because the surrounding four sides of the external static zone are set as wall attributes, the space of the external static zone needs to be set as large as possible to prevent the wall from affecting the development of the UAV downwash field near the ground. In this paper, the size of the external static zone is set to $16\text{ m} \times 16\text{ m} \times 8\text{ m}$. The four dynamic domains are in the positive center of the static domain, and the coordinate axes of the Cartesian coordinate system of the UAV are parallel to the edges of the external static domain. As shown in Figure 5, a polygonal mesh is used. After fluent meshing is used to draw the mesh, the total number of meshes in the external static domain is 913,171; the total number of meshes in the four dynamic domains is 93,408, 92,891, 93,396 and 92,873; and the total number of meshes in the model is 1,285,739. It was demonstrated by [33] that the number of grids has little effect on the simulation results. This study successively established two simulation models with different mesh quantities for the three-dimensional model of the research subject, with mesh quantities of 1,265,190 and 2,686,674, respectively. The downwash airflow velocity at fixed points within the models was inspected. The results showed that the simulation model with 1,265,190 meshes calculated a downwash airflow velocity of 1.27 m/s, and the simulation model with 2,686,674 meshes also calculated downwash airflow velocity of 1.32 m/s, only 0.05 m/s of difference. This further demonstrates that the quantity of the mesh does not affect the accuracy of the simulation.

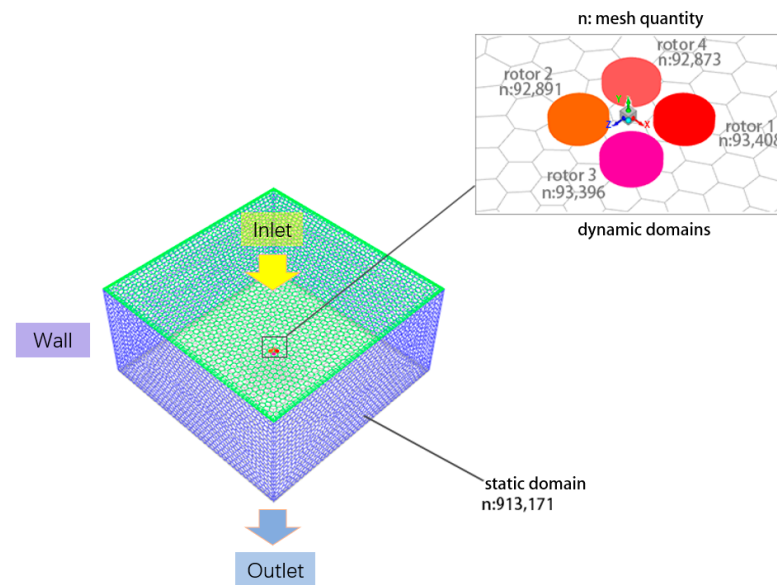


Figure 5. Simulation mesh model.

3.1.3. Setting the Simulation Parameters

Based on the mesh model, the simulation calculation parameters are set. Regarding the simulation parameter settings, the main control equation of the simulation model adopts the average Navier–Stokes equation, which is mainstream in the industry, and its expression in the rectangular coordinate system is as follows:

$$\rho \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \omega \frac{\partial u}{\partial z} \right) = \rho f_x - \frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad (1)$$

$$\rho \left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + \omega \frac{\partial v}{\partial z} \right) = \rho f_y - \frac{\partial p}{\partial y} + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \quad (2)$$

$$\rho \left(\frac{\partial \omega}{\partial t} + u \frac{\partial \omega}{\partial x} + v \frac{\partial \omega}{\partial y} + \omega \frac{\partial \omega}{\partial z} \right) = \rho f_z - \frac{\partial p}{\partial z} + \mu \left(\frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2} + \frac{\partial^2 \omega}{\partial z^2} \right) \quad (3)$$

In these equations, x , y , and z are the Cartesian coordinate system coordinates along the edges and corners of the fluid volume element; ρ is the fluid density; u , v , and ω are the velocity components at the positions of x , y , and z of the coordinate system at time t , respectively; f_n ($n = x, y, z$) is the external force on the fluid volume element in this direction; p is the pressure on the fluid volume element; and μ is a constant expressing the dynamic viscosity. The main control equations are used to obtain the various properties of the fluid in all directions.

The turbulence model used is the realizable k - ϵ turbulence model, which is expressed in a rectangular coordinate system as follows:

$$\frac{\partial(\rho K)}{\partial t} + \frac{\partial(\rho \bar{u}_j k)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\delta_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \epsilon - Y_M + S_k \quad (4)$$

$$\frac{\partial(\rho \epsilon)}{\partial t} + \frac{\partial(\rho \epsilon u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\delta_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + \rho C_1 S \epsilon - C_2 \rho \frac{\epsilon^2}{K + \sqrt{v \epsilon}} + C_{1\epsilon} \frac{\epsilon}{k} C_{3\epsilon} G_b + S_\epsilon \quad (5)$$

Among the variables, G_k is the turbulent kinetic energy, G_b is the turbulent kinetic energy due to buoyancy, and μ_t is the eddy viscosity. The parameters are as follows:

$$C_1 = \max\left[0.43, \frac{\eta}{\eta+5}\right], \eta = \frac{k}{\varepsilon} S, S = \sqrt{2S_{ij}S_{ij}}; C_{1\varepsilon} = 1.44; C_{2\varepsilon} = 1.68; \delta_\varepsilon = 1.2; \delta_k = 1.0; \text{ and } C_2 = 1.9.$$

3.2. Validation Experiment Materials and Methods

To judge whether the simulation calculation parameters are set correctly or not, it is necessary to compare the results of the simulation calculation with the validation experiment. In contrast to using downwash airflow velocity sensors in the validation experiments in previous studies, a new verification method that no longer focuses on the downwash airflow velocity values in the wind field but on the boundary of the wind field in the space below the UAV is proposed in this paper. This verification method uses the follow-through of light and small objects in the wind field to visualize the wind field boundary and study the related characteristics. The light and small object selected in this paper is an EPS (expanded polystyrene foam) ball. On the one hand, the sphere structure has good mechanical characteristics, as shown in the geometric space, and the projection of the sphere in any direction is consistent. Thus, the sphere is affected by the wind in all directions; that is, the effects of the wind field forces in all directions on the sphere tend to be the same. On the other hand, the EPS is a lightweight material, generally ranging from 10 to 45 kg/m³, which can detect the effect of a slight wind field force. As shown in Figure 6, the motion state of the ball inside and outside the downwash field is captured by the camera; then, the images are inputted into the video software for frame-by-frame analysis. Twenty frames of the ball at two positions are extracted for comparison. It was found that when the EPS ball was in the downwash field, it was affected by the downwash field, and the ball showed a continuous swing in the time domain. In Frame 5, the ball is to the right of the centerline. In Frames 10–15, the ball swings to the left of the centerline. In Frame 20, the ball swings back to the right side of the ball. When the EPS ball is outside the downwash field of the UAV, the ball appears to be stationary near the centerline from Frames 5 to 20. Moreover, the neighboring small balls are in different states. That is, when a small ball swings continuously and the other small ball is stationary, the boundary of the downwash field is between the two small balls.

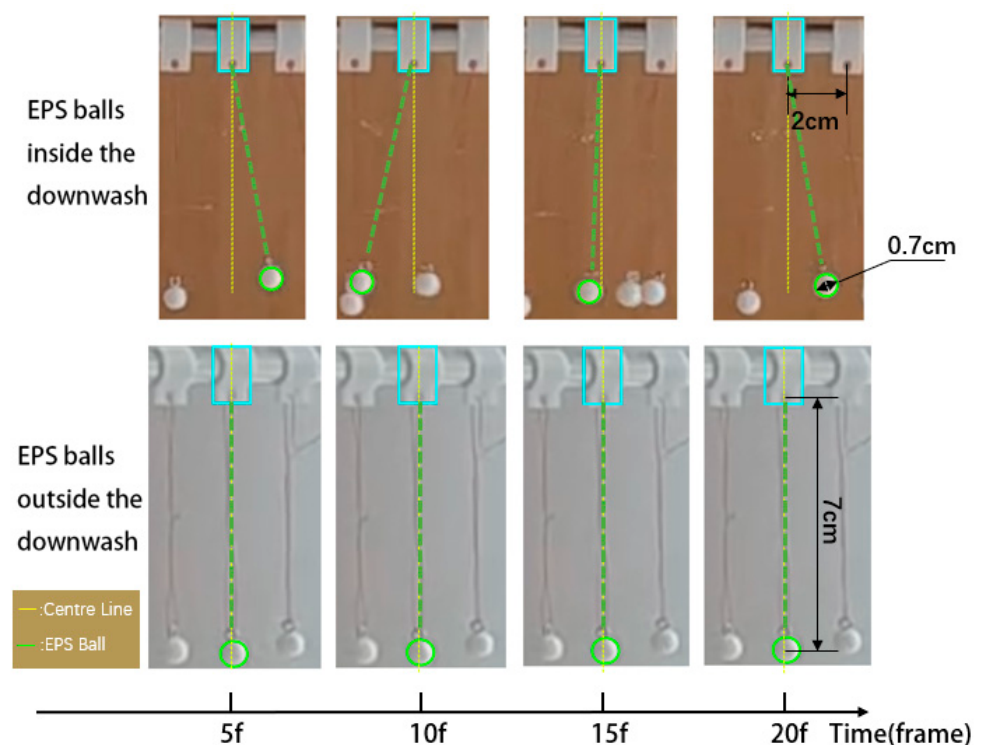


Figure 6. Inside and outside states of the EPS ball in the downwash field of the UAV (f is the frames).

Notably, the test ball is not ideal; it still has some weight, and the inertia of the ball itself will prevent the small ball from swinging. Before the validation experiment, a pre-experiment is conducted to test the starting downwash airflow velocity of the EPS ball. As shown in Figure 7, because the centrifugal pump has the characteristics of stable work and continuous output, a stable wind generator is designed according to its structure. After testing, the stable wind generator can generate a stable downwash airflow velocity. A single small ball is suspended 5 cm below the stable wind generator. By adjusting the downwash airflow velocity generated by the generator, the downwash airflow velocity value of the ball is measured by the impeller downwash airflow velocity sensor when the ball is stationary.

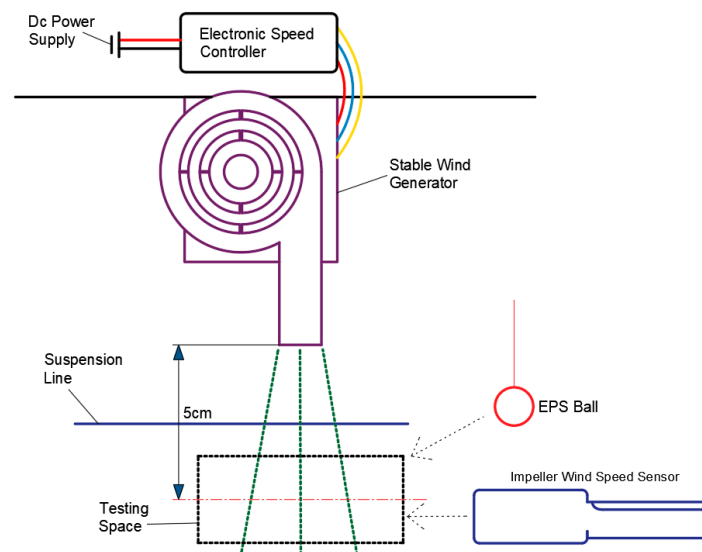


Figure 7. The ball starting downwash airflow velocity measuring device.

The downwash airflow velocity value is measured by the HP-866B-WM wind speed sensor (Holdpeak, Zhuhai, China), which has a wind speed measurement range of 0.3 m/s to 30 m/s. Through multiple measurements, as shown in Table 4, when the downwash airflow velocity value is 0.3 m/s, the small ball is still in the swing state. Due to the limitation of the test instrument, downwash airflow velocity less than 0.3 m/s cannot be displayed. Because 0.3 m/s is close to the static downwash airflow velocity specified in *Environmental Science* (0–0.2 m/s) [34], it is considered that the starting downwash airflow velocity of the small ball is close to the static downwash airflow velocity, which further indicates that the selected EPS small ball is sufficiently light.

Based on the significant features expressed by the EPS balls concerning different downwash airflow velocity, a specific wind field range detection scheme is designed in this paper. As shown in Figure 8, the verification device consists of four parts: the support frame, the UAV carrying platform, the test device, and the camera. The test device is divided into a mobile base, mobile connection flange, test rod, and EPS balls. To provide the UAV with as much development space as possible for the downwash field, the support frame is made with a test space of 1500 mm × 1500 mm × 2500 mm. The UAV carrying platform can move in the vertical direction of the support frame. The test rod with a length of 2 m is connected to the mobile base on both sides by a mobile connection flange, which constitutes the whole test device. The test device is independent of the support frame and can move freely in the test space formed by the support frame. The camera is positioned directly against the test rod so that it can capture the whole test rod completely. A 7 mm diameter EPS ball is used as the test ball, and an installation space of 4 cm is left on both sides of the test rod. To ensure that there is sufficient swing space between the balls and sufficient data volume for the whole test rod, 96 test balls are suspended on the test rod at an interval of 2 cm. To prevent the test rod from affecting the downwash field development

and ensure its hardness, the test rod uses an aluminum hollow tube with a diameter of 1 cm. The test rod is mounted on a mobile base with a mobile connector and can be vertically moved up and down on the base.

Table 4. Relationship between the ball state and downwash airflow velocity.

	Average Down-wash Airflow Velocity within 10 s	Swing Period (Frame)	Average Down-wash Airflow Velocity within 10 s	Swing Period (Frame)	Average Down-wash Airflow Velocity within 10 s	Swing Period (Frame)	Average Down-wash Airflow Velocity within 10 s	Swing Period (Frame)	Average Down-wash Airflow Velocity within 10 s	Swing Period (Frame)
1	0.30 m/s	23	0.67 m/s	20	0.89 m/s	12	1.77 m/s	12	1.99 m/s	7
2		22		20		11		20		7
3		21		18		16		12		7
4		22		16		17		6		7
5		18		16		14		17		8
6		21		15		17		18		12
7		20		15		17		8		11
8		17		21		16		14		10
9		22		23		17		12		11
10		16		20		18		14		8
11		23		18		14		11		7
12		20		21		20		10		7
13		21		21		17		12		9
14		20		15		15		10		9
15		18		16		17		14		9
16		22		20		17		12		9
Average swing period		20.375		18.4375		15.9375		12.625		8.625

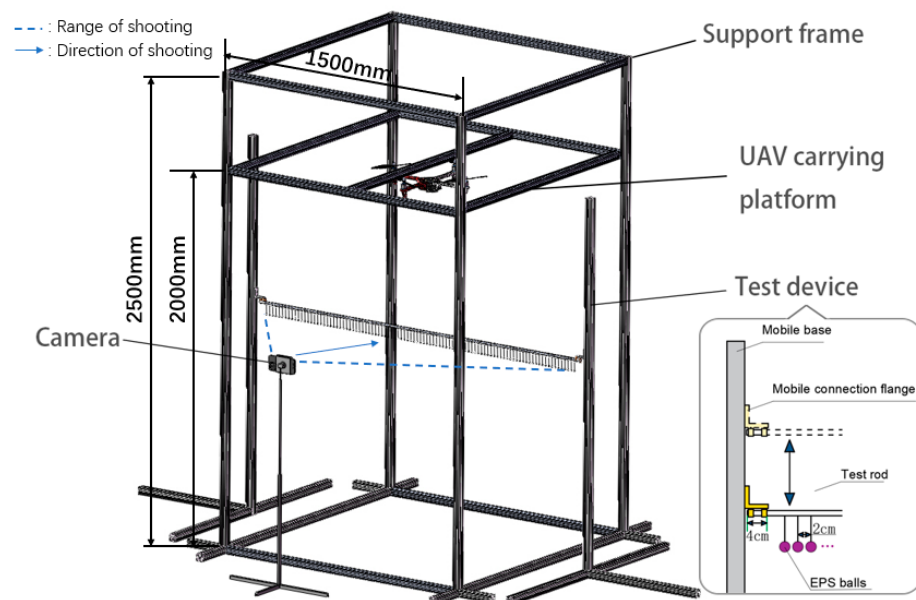


Figure 8. Wind field range validation device.

As shown in Figure 9, in the validation test, the DJIF450 UAV is installed on the UAV carrying platform, and the UAV rotor plane is 2 m from the ground to be consistent with the environment setting during the simulation calculation. A throttle value of 50% is often used in DJIF45 UAVs during operation, corresponding to a rotation speed of each rotor

of approximately 2000 rpm. Therefore, 2000 rpm is set for each rotor in the simulation parameter setting and experimental parameter setting. In this paper, the UAV lower space is divided into two parts, the rotor lower space and the non-rotor lower space, where the rotor lower space can be divided into the Rotor 1 and 3 lower spaces and the Rotor 2 and 4 lower spaces. To make the whole wind field verification representative, a numerical plane is selected in the lower space of the UAV rotor for testing. The plane is selected to go through the Rotor 1 and 3 (plane β) vertical plane, the Rotor 2 and 4 (plane α) vertical plane in the rotor lower space, and three points, $(0.75 \text{ m}, -2 \text{ m}, 0.5 \text{ m})$, $(-0.75 \text{ m}, -2 \text{ m}, -0.5 \text{ m})$, and $(0.75 \text{ m}, 0 \text{ m}, 0.5 \text{ m})$, to construct a plane (plane γ) in the non-rotor lower space. To ensure that the downwash field boundary measurements have a certain resolution and sufficient identification between each other, the center of the UAV is taken as the reference (Y-axis origin) in each plane, the upward direction is the positive direction of the Y-axis, and 0.2 m is taken as a unit. The downwash field range at -0.2 m , -0.4 m , -0.6 m , -0.8 m , -1 m , -1.2 m , and -1.4 m from the UAV plane is measured.

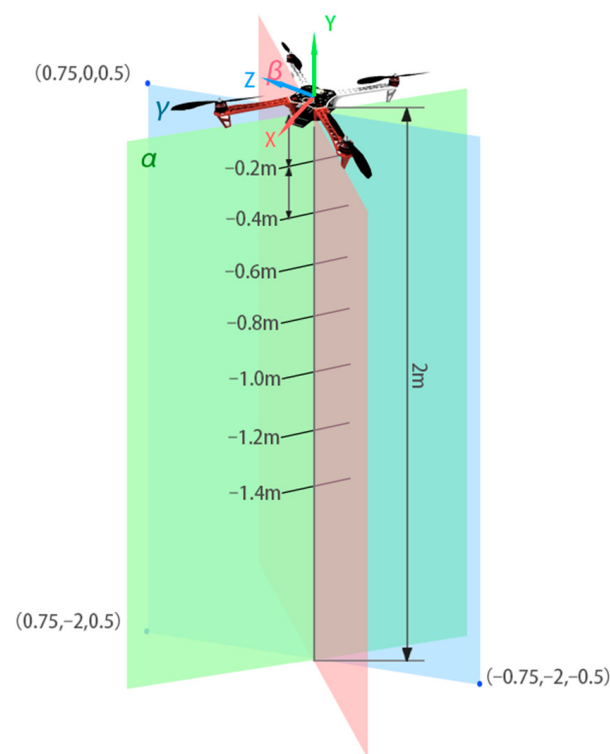


Figure 9. Experimental test setup diagram.

During the experiment, the UAV needs a stable voltage for a long time to maintain the rotor speed, and the aviation battery cannot work for a long time. The DC-regulated power supply of Annes Power Co., Ltd. (Wuxi, China) is used to provide a stable 12 V voltage to each electronic speed control (ESC) through the sub-board for a long time to meet the experimental requirements. The DC-regulated power supply parameters are shown in Table 5, which shows the supply can provide stable voltage and current for a long time.

Table 5. JP60300D DC-regulated power supply parameters.

Model	JP60300D
Working mode	Work continuously for long hours
Accuracy of the voltage regulation	Source effect $\leq 0.5\%$ rating; load effect 0.5%
Accuracy of steady flow	Source effect $\leq 0.5\%$ rating; load effect 0.5%
Time drift	Continuous work for more than 8 h $\leq 0.5\%$ rating
Temperature drift	$\leq 0.05\%$ rating/ $^{\circ}\text{C}$

After the UAV runs stably for 10 s, the downwash field boundary of each plane and the height of the UAV will be tested in turn. As shown in Figure 8, the camera records the motion state of the swing ESP ball for 30 s. The motion state of the ball will be analyzed frame by frame through the video software to obtain the downwash field range of the measurement height.

3.3. Experiment on the Relationship between Spray Deposition and Wind Field Range

The accuracy of the simulation results is verified by comparing the downwash field range of the measured height in the validation test and the simulation results. After verifying the accuracy of the simulation results, the simulation data are used to analyze the downwash airflow velocity characteristics and the wind field range of the UAV downwash field. To explore the relationship between downwash airflow velocity characteristics, downwash field range, and spray deposition, this study designs an experiment for the correlation between spray deposition and downwash field. As shown in Figure 10, the spraying system and testing platform are added to the original downwash field range verification device in this study. As shown in Figure 11, the spraying system is composed of control and detection modules, a water pump, a pressure regulator valve, a solenoid valve, and nozzles. The detection module includes a power supply, switch, voltage regulating module, and single-chip microcomputer. The KZ0804 (LICHENG, Ningbo, China) hydraulic conical nozzle is installed under each rotor. The test plane is set at 0.8 m from the UAV rotor plane. The height setting plane is selected because, at this height, the range of droplet spraying will not exceed the range of the support frame, and it is easy to repeat the experiment.



Figure 10. Experimental test setup diagram.

As shown in Figure 12, in the plane of 1500 mm × 1500 mm, taking directly below the center of the UAV as the reference point, a collection point is set every 20 mm, the parallel X-axis is defined as the column, the vertical X-axis is defined as the row, each row and column has 7 collection points, and a total of 49 collection points are set. A measuring cup with a total range of 30 mL is placed at each collection point to collect the spray droplets. To facilitate the subsequent reading of data and statistical results, a number is set for each collection point and written on the measuring cup.

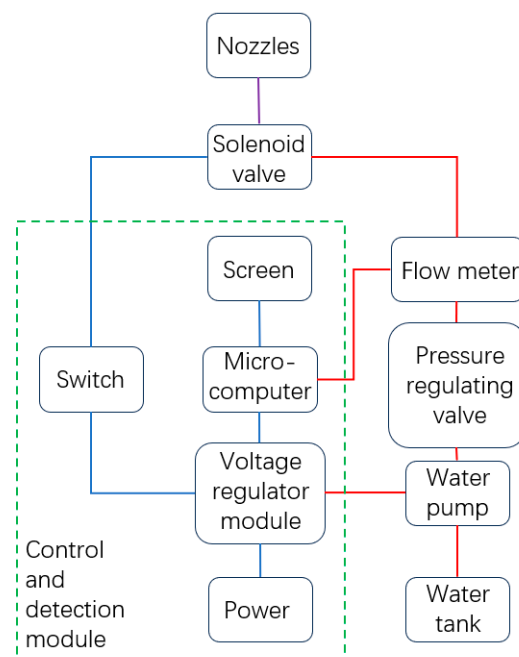


Figure 11. Experimental test setup diagram.

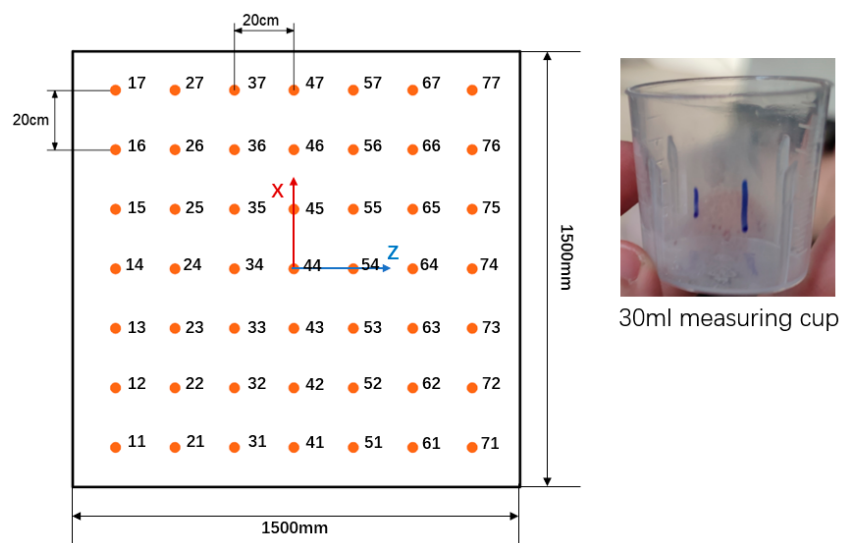


Figure 12. Collection point setting.

During the experiment, to ensure the accuracy of the experiment, the UAV is started first, and the spraying system is started after the rotor speed is stable. In the UAV operations, the pressure of droplet spraying is generally 0.3 Mpa to 0.5 Mpa. The higher the pressure, the greater the initial velocity of the droplets and the larger the spraying range, which is difficult to be affected by the downwash field of the UAV. In this paper, to explore the influence of the downwash field of the UAV on the deposition of droplets in the limit case, the spraying pressure is set to 0.5 Mpa, and the inlet injection conditions are shown in Table 6. To ensure that enough droplets are deposited in the measuring cup for statistics, the spraying time is set at 2 min. The relationship between the range of the downwash field and the deposition of droplets is explored by statistical analysis of the deposition amount of droplets in the collection points.

Table 6. Inlet injection conditions of the JIACHENG KZ0804 hydraulic conical nozzle.

Name	Parameter Values
Spray angle	80°
Spray angle	0.5 Mpa (5 bar)
Flow rate	0.52 L/min
Atmospheric temperatures	22 °C
Atmospheric pressure	1001 hpa

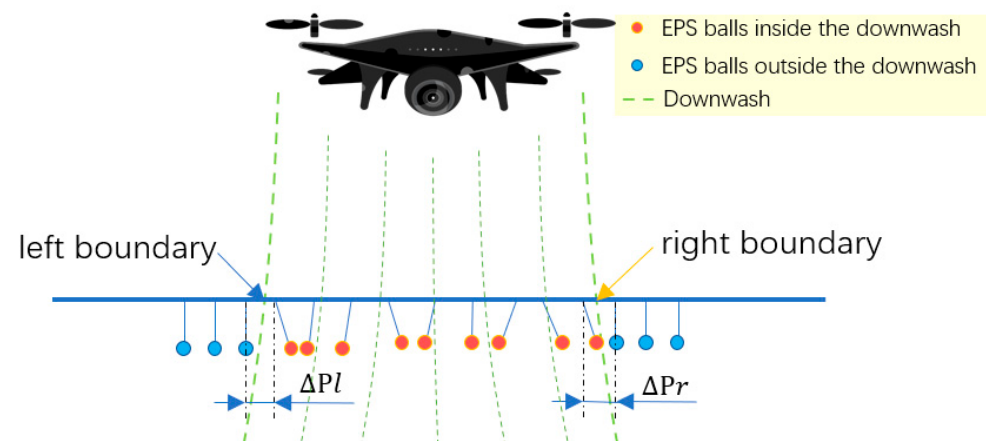
4. Results and Analysis

4.1. Accuracy Verification of the Simulation Results

Before verifying the accuracy of the simulation results, it is necessary to define the boundary of the downwash field in the validation experiment, as shown in Figure 13. When the neighboring small balls with spacing ΔP ($\Delta P = \Delta Pl = \Delta Pr$) are in different states, the boundary of the downwash field is between the two neighboring small balls. In a single plane at a single height, the downwash field range consists of the left boundary and the right boundary (where the left boundary lies in ΔPl and the right boundary lies in ΔPr), and the distance between the left boundary and the right boundary is the downwash field range of the plane at that height. However, since the left and right boundaries are between a small section of the region with ΔP as the range, the left and right boundaries may be at any position in region ΔP , so the middle value of ΔP is taken as the boundary value of the left and right boundaries; that is, the calculation formula of D_{Area} of the downwash field range is as follows:

$$D_{Area} = \frac{\Delta Pl}{2} + \frac{\Delta Pr}{2} + (\Delta P \times N) = [\Delta P \times (N + 1)] \quad (6)$$

where N is the number of small balls in the downwash field.

**Figure 13.** Schematic diagram of the boundary of the downwash field.

As shown in Figure 14, the UAV downwash field in the simulation results is sampled. Taking the α plane as an example, the sampling method is to make 0.8 m sampling lines on both sides of the Y-axis perpendicular to the center directly below the UAV at a single height, and 500 points are sampled on the line. The distance between each line is 0.2 m, so there are seven detection lines in total. The points below and closest to the downwash airflow velocity of 0.3 m/s are selected online as the left and right boundary points, and the distance between the left and right boundary points is the downwash field range of the plane at the same height. By comparing the simulation calculated downwash field boundary value and the actual measured downwash field boundary value along these seven sampling lines and calculating the error, the accuracy of the simulation calculations can be verified through the analysis of the error.

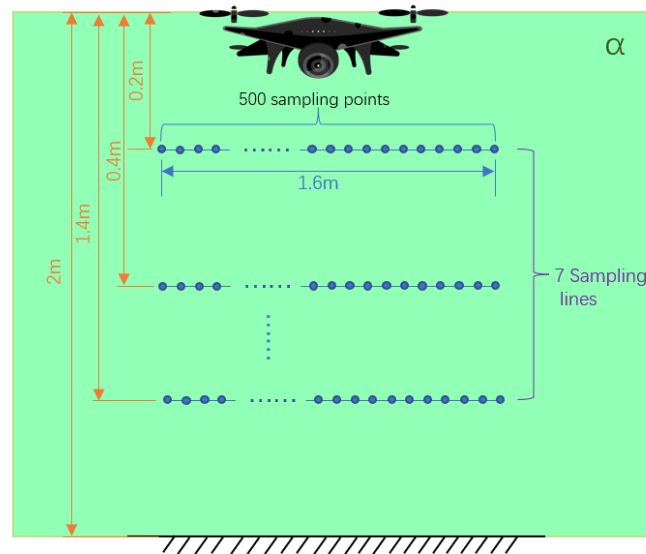


Figure 14. Sampling points of the simulation results.

The error is calculated as follows:

$$e = \frac{|l_r - l|}{l_r} \times 100\% \quad (7)$$

where e is the error, l_r is the actual measured downwash field boundary value, and l is the simulation calculated downwash field boundary value. The comparison between the validation experiment data and the simulation calculated data is shown in Table 7.

Table 7. Comparison of the simulation data with the measured data of each section.

Distance(m)	Test Plane	l_r (cm)	l (cm)	e	Test Plane	l_r (cm)	l (cm)	e	Test Plane	l_r (cm)	l (cm)	e
0.2	α	70	74.31	6.16%	β	72	74.63	3.65%	γ	70	67.12	4.11%
0.4	α	74	76.24	3.03%	β	72	76.25	5.90%	γ	70	71.63	2.33%
0.6	α	72	74.96	4.11%	β	80	75.6	5.50%	γ	76	77.05	1.38%
0.8	α	80	77.22	3.48%	β	82	77.54	5.44%	γ	82	81.26	0.90%
1	α	90	84.32	6.31%	β	86	82.39	4.20%	γ	92	89.69	2.51%
1.2	α	92	93.7	1.85%	β	98	93.05	5.05%	γ	98	101.42	3.49%
1.4	α	102	101.45	0.54%	β	102	101.12	0.86%	γ	102	104.74	2.69%

The maximum error between the experimental measurement value and the simulation value does not exceed 10%, and the simulation value is consistent with the experimental measurement value, so the simulation results can be considered credible. Notably, the possible reason for the large error value of some data, like 6.16% and 6.31%, is that a completely wind-free environment cannot be created in the actual experiment, and the natural wind may cause the ball to swing. According to the table, as the distance from the UAV rotor plane increases, the simulation data and the experimental data are consistent in the trend of downwash field expansion. In the α plane, the simulation data for the wind field range increases from 74.31 cm to 101.45 cm, and the experimental result increases from 70 cm to 102 cm. In the β plane, the simulation result for the wind field range increases from 74.63 cm to 101.12 cm, and the experimental value increases from 72 cm to 102 cm. In the γ plane, the simulation value for the wind field range increases from 67.12 cm to 104.74 cm, and the experimental value increases from 70 cm to 102 cm. However, since the experimental data can only show this feature in three planes in the lower space of the UAV, further regularity analysis will be carried out on the simulation results to explore whether the conclusion applies to the whole space below the UAV.

4.2. Analysis of Simulation Results

The simulation results were post-processed by using CFD-POST extraction to obtain cross-section contour images of planes α , β , and γ to observe the overall shape of the downwash field, as shown in Figure 15. Combined with Table 7, it can be found that the downwash field in the negative half-axis of the Y-axis presents a diffusion state. Near the center of the UAV, the contour appears blue, which means that the downwash airflow velocity is lower in this area.

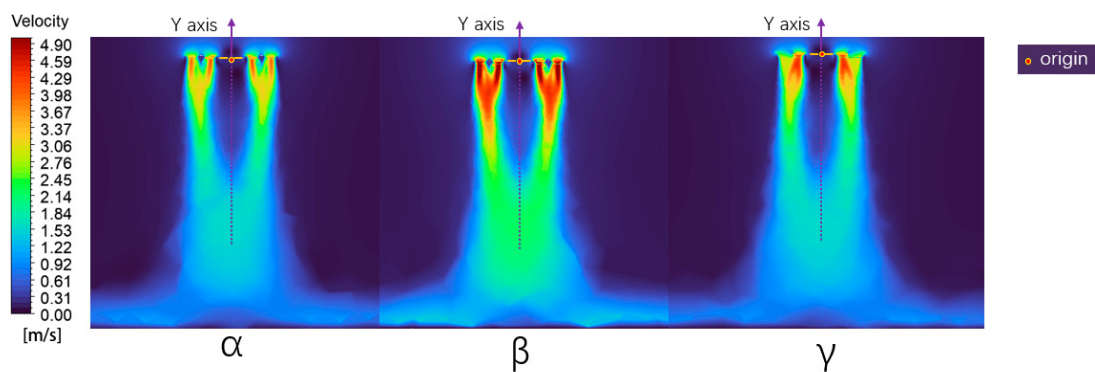


Figure 15. Longitudinal contour map of the downwash field.

The line chart of the downwash airflow velocity data at the plane sampling point further illustrates this point, as shown in Figure 16. At a position -0.2 m away from the origin along the Y-axis, the minimum downwash airflow velocity is 0.21 m/s in the α plane, 0.21 m/s in the β plane, and 0.21 m/s in the γ plane. When the Y-axis is at -0.4 m, the minimum downwash airflow velocity of each plane increases to 0.45 m/s. In the three planes, when $Y > -1.0$ m, the downwash airflow velocity below the origin of the UAV is lower than the downwash airflow velocity below the rotor, and when -2.0 m $< Y < -1.0$ m, the downwash airflow velocity below the origin of the UAV gradually becomes higher than the downwash airflow velocity below the rotor.

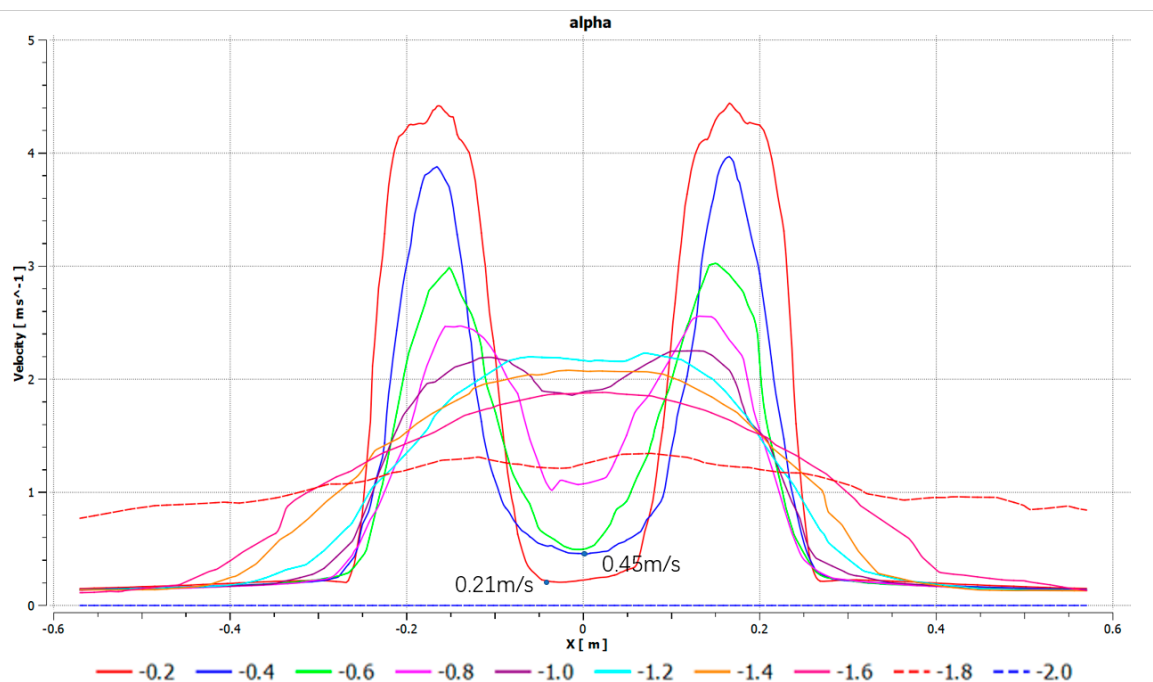


Figure 16. Cont.

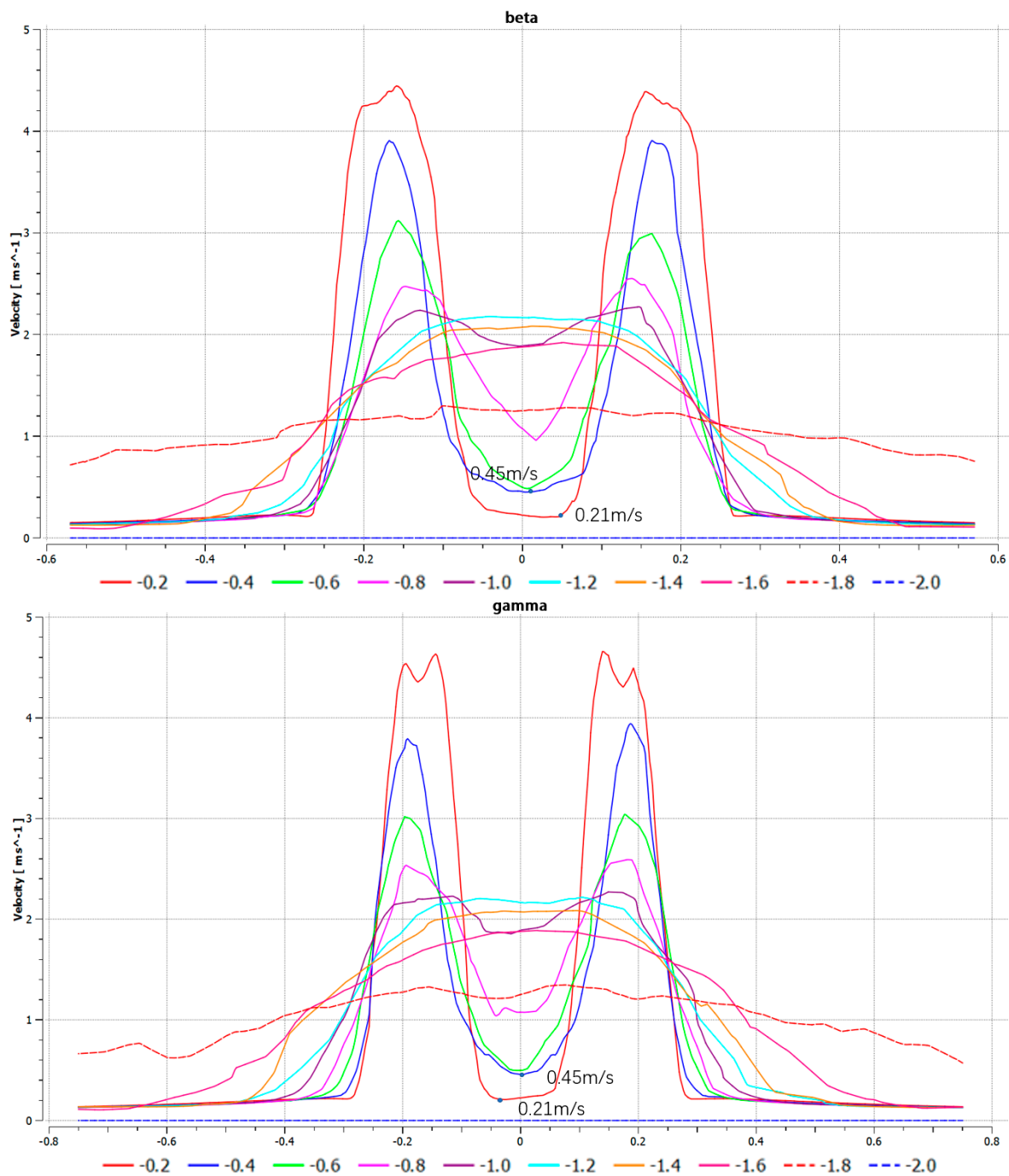


Figure 16. Downwash airflow velocity distribution on the Y-axis of planes α , β , and γ .

This rule that the low wind velocity appears at the center of the UAV near the rotor is also reflected in the horizontal section of the downwash field, which is the area and shape of the cross section of the downwash field. Figure 17 shows the horizontal cross-section contour images 0.2 m, 0.6 m, 1 m, 1.2, 1.4 m, 1.8 m from the UAV rotor plane obtained by CFD-POST. In general, we found some special boundary shapes that have not been reported in previous studies.

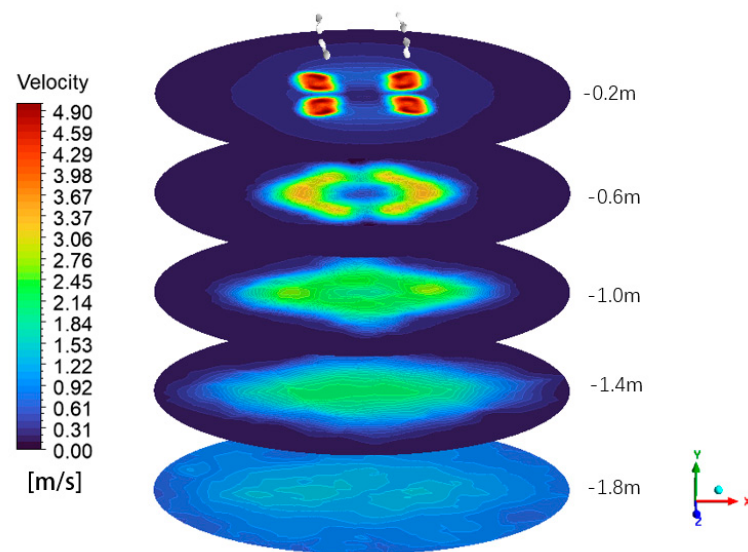


Figure 17. Horizontal contour diagram of the downwash field in simulation calculations.

The cross-section contour image data are imported into the origin, and through data screening, the downwash airflow velocity data in each section are divided into sections a and b with 1 m/s as the boundary, where $0 \text{ m/s} < a < 1 \text{ m/s}$, 0.2 m/s is a unit and four downwash airflow velocity levels of 0.2 m/s, 0.4 m/s, 0.6 m/s, and 0.8 m/s exist. When $1 \text{ m/s} < b < 5 \text{ m/s}$, 1 m/s is a unit divided into 1 m/s, 2 m/s, 3 m/s, 4 m/s, and 5 m/s wind levels. By drawing scatter diagrams of different downwash airflow velocities in the cross sections, the broken line diagram is synthesized, and then the cross-sectional area of the downwash field is calculated by using the Origin mathematical analysis tool “closed curve area” at the downwash airflow velocity level, as shown in Table 5 and Figure 18. In the graph, the data for 1.8 m have been removed to enhance the clarity of the image, as they significantly deviate from the other data.

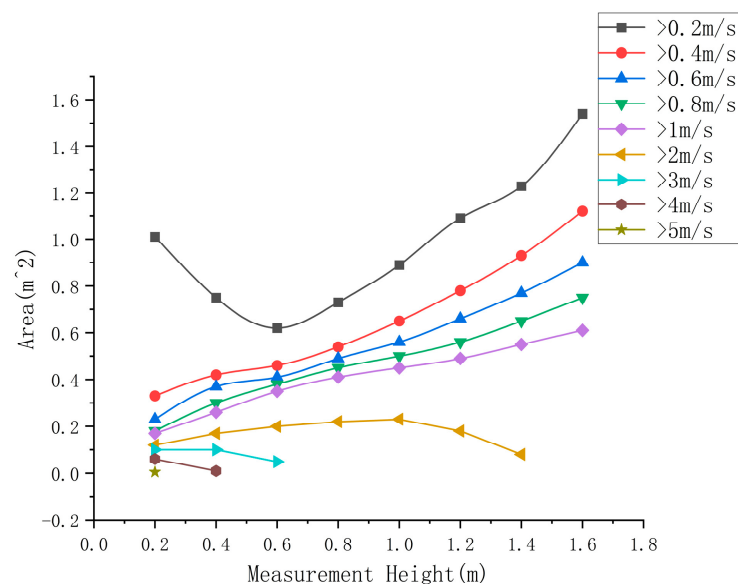


Figure 18. Downwash field area of different downwash airflow velocities at each height.

To more intuitively describe the change law of the area enclosed by the downwash airflow velocity boundary of each height section of the UAV downwash field, in the expansion (contraction) section of wind field area, the change rate of wind field area under each downwash airflow velocity is defined as follows:

$$\eta_{\text{exp(con)}} = \frac{A_{\text{max}} - A_{\text{min}}}{|h_1 - h_2|} \times 100\% \quad (8)$$

where η_{exp} and η_{con} are the expansion and contraction rates of the downwash field area, respectively; A_{max} is the maximum downwash field area in the expansion (contraction) segment of the downwash field; A_{min} is the minimum downwash field area in the expansion (contraction) segment of the downwash field; and h_1 and h_2 are the beginning and end heights of the expansion (contraction) segment of the downwash field, respectively.

Among the downwash airflow velocity boundaries less than or equal to 1 m/s, except for 0.2 m/s, the remaining downwash airflow velocity boundaries are gradually expanded in the development of the downwash field. The downwash field area with 1 m/s, 0.8 m/s, 0.6 m/s, and 0.4 m/s downwash airflow velocity as the boundary expands by 0.712 m², 1.72 m², 5.81 m², and 36.87 m², respectively, from the UAV rotor plane to 1.8 m out of the plane. The expansion rates η_{exp} are 40%, 95.56%, 322.78%, and 2048.33%, respectively. The downwash field with the boundary of a 0.2 m/s downwash airflow velocity shrinks from 0.2 m to 0.6 m, shrinking by 0.39 m², where η_{con} is 38.61%, and the area expands from 0.6 m to 1.8 m (as shown in Figure 14), expanding by 174.22 m², and η_{exp} is 14518.33%. It can be concluded that when the downwash airflow velocity is lower, it is easier for flow separation to occur, and the rate of expansion of the wind field area is faster (as shown in Table 8 and Figure 18).

Table 8. Wind field area (m²) of different height cross sections with different downwash airflow velocities (m/s).

	>0.2 m/s	>0.4 m/s	>0.6 m/s	>0.8 m/s	>1 m/s	>2 m/s	>3 m/s	>4 m/s	>5 m/s
0.2 m	1.01	0.33	0.23	0.18	0.17	0.12	0.10	0.06	0.0046
0.4 m	0.75	0.42	0.37	0.30	0.26	0.17	0.10	0.0095	
0.6 m	0.62	0.46	0.41	0.38	0.35	0.2	0.049		
0.8 m	0.73	0.54	0.49	0.45	0.41	0.22			
1 m	0.89	0.65	0.56	0.50	0.45	0.23			
1.2 m	1.09	0.78	0.66	0.56	0.49	0.18			
1.4 m	1.23	0.93	0.77	0.65	0.55	0.08			
1.6 m	1.54	1.12	0.90	0.75	0.61				
1.8 m	174.84	36.87	5.81	1.72	0.72				

Among the downwash airflow velocity boundaries greater than 1 m/s, except for 2 m/s, the remaining downwash airflow velocity boundaries gradually shrink in the development of the downwash field. The downwash field areas with 3 m/s, 4 m/s, and 5 m/s downwash airflow velocity boundaries shrink by 0.10 m², 0.06 m², and 0.0046 m², respectively, from the UAV rotor plane to the disappearance of the downwash airflow velocity boundary. The η_{con} values are 16.67%, 15%, and 2.3%, respectively. The downwash field with the boundary of 2 m/s downwash airflow velocity expands from 0 m to 1.0 m, with an expansion of 0.23 m² and η_{exp} of 23%. Moreover, it contracts from 1.0 m to 1.6 m, with a contraction of 0.23 m² and η_{con} of 38.33%. It can be concluded that when the downwash airflow velocity decreases, the downwash field area contraction rate of the downwash airflow velocity has no obvious law.

The nature of the expansion and contraction of the downwash field area is reflected in the change in the downwash airflow velocity on the Y-axis. Any gas in space is converted into the internal energy of molecular movement because of the mutual friction between molecules. Moreover, the kinetic energy of gas downward movement is reduced, the downwash airflow velocity is reduced, the area of high downwash airflow velocity shrinks

or disappears and is converted into a low downwash airflow velocity area, and the area of low downwash airflow velocity expands [35]. Near the rotor plane, the airflow, as a result of the rotor's rotation, possesses significant tangential kinetic energy; hence, even the low downwash airflow velocity areas, such as those at 0.2 m/s, will also expand. Thus, the wind field area of 0.2 m/s will first decrease and then increase.

It can be explained that the high downwash airflow velocity area cannot be developed to the ground in the development of the UAV downwash field, as shown in Figure 19, which show the boundary map of the downwash field is composed of the positions of various wind velocities extracted from the simulation results. Each downwash field at the position -0.2 m away from the Y-axis has just developed from each rotor; at this time, the downwash airflow velocity of 5 m/s exists below each rotor, the wind field has high kinetic energy, the downward development trend is strong, and the low downwash airflow velocity area appears in the center of the UAV. The wind field presents a “four-point pattern”. When the downwash field develops -0.4 m from the Y-axis, because the vortex dissipation caused by the vortex generated by the rotor airflow cuts down the overall airflow kinetic energy of the downwash wind field, the airflow separation is more serious, so the overall downwash wind field shows a diffuse trend [35], the downwash airflow velocity of 5 m/s disappears, and the downwash field below each rotor begins to spread due to energy consumption. Therefore, the low downwash airflow velocity area can no longer be maintained below each rotor and starts to become a whole area. For example, the downwash airflow velocity boundary of 1 m/s is changed from a “four-point type” to “square-like”. However, the wind field cross section at downwash airflow velocity boundaries of 2 m/s, 3 m/s, and 4 m/s still shows a “four-point type”. When the wind field develops at positions from -0.4 m to -0.6 m from the Y-axis, the downwash airflow velocities of 3 m/s and 4 m/s disappear. At this time, only downwash airflow velocities below 2 m/s are present in the wind field, which contains lower kinetic energy and spreads more thoroughly. The overall shape of the wind field is “ellipse-like”.

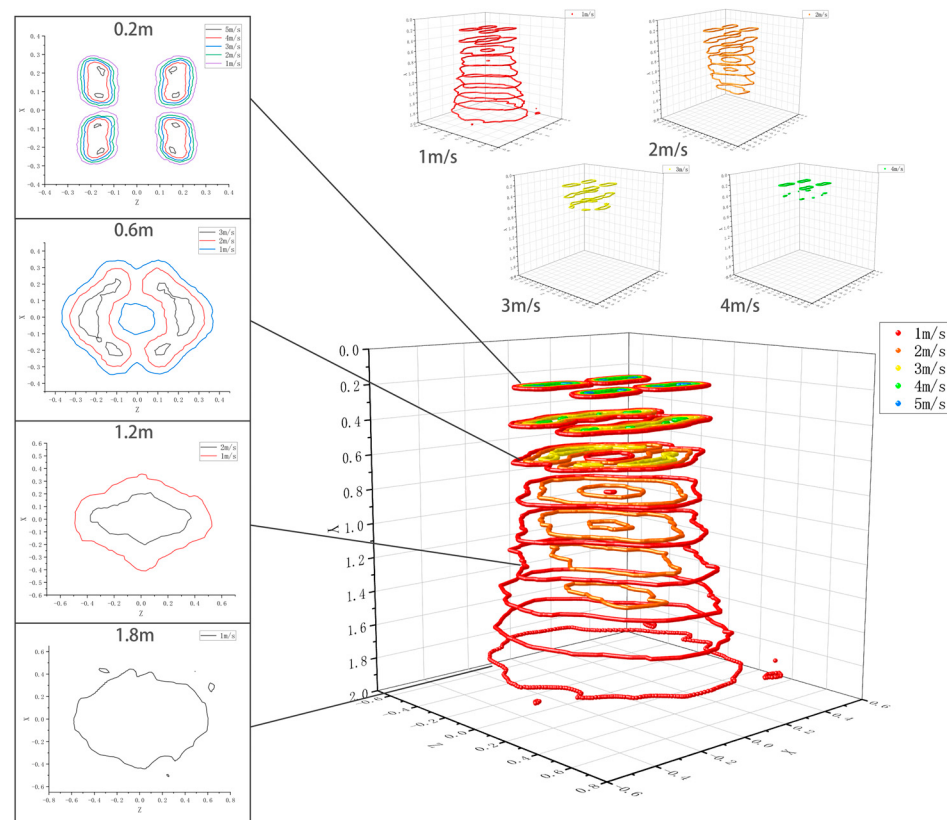
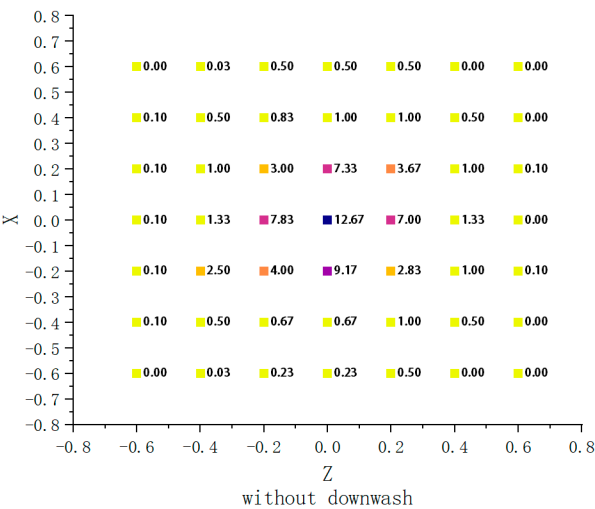
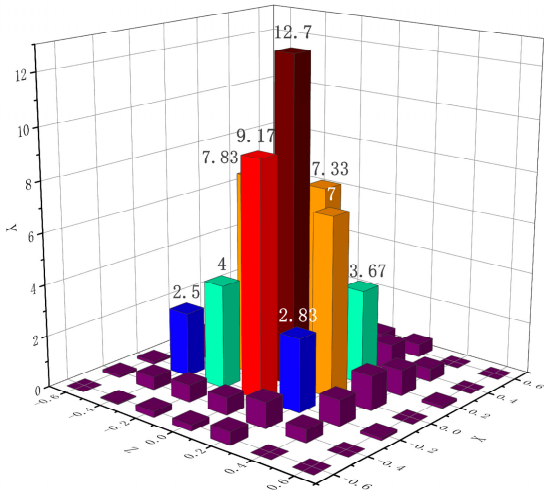


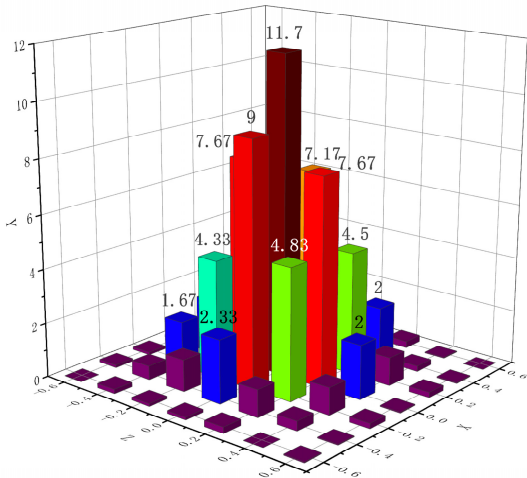
Figure 19. The boundary map of the downwash field extracted from the simulation results.



(b) spray deposition distribution without downwash filed



(c) spray deposition distribution without downwash filed(bar chart)



(d) spray deposition distribution with 2000rpm downwash filed(bar chart)

Figure 20. Relationship between the 2000 rpm downwash field and spray deposition.

To explore whether this distribution of droplets is the result of the effect of the downwash field of the UAV, a control test is set up in this study. The spraying experiment was carried out for 2 min without turning on the UAV and repeated three times. The atmospheric temperature during the experiment was 22 °C, and the atmospheric pressure was 1001 hPa. In the three tests, the total liquid volume deposited at the collection points was 80.55 mL, 79.5 mL, and 79 mL, respectively, with an average of 79.68 mL. In each of the three experiments, the total amount of droplets deposited at the center nine collection points was 57.5 mL, accounting for 71.38%, 72.33%, and 72.78% of the total deposition of the 49 collection points, respectively, with an average of 72.16%.

Comparing the two cases with and without the UAV downwash field, as shown in Figure 20, it can be seen that the deposition amount of droplets in the center nine collection points of the 2000 rpm downwash field is more than that in the same field without the UAV downwash field. In the three experiments, the total amount of spray deposition at these nine collection points increased by 6.38% on average. It is worth noting that the deposition of droplets at the central collection point decreased by 7.87% compared with the case of no downwash field. From the bar chart in Figure 20c,d, it can be observed that in the presence of the UAV downwash field, compared to the absence of the UAV wind field, the differences between each bar are smaller and there is more total spray deposition volume among all the collection points. This means that the deposition of droplets at the central collection points will be more uniform in the presence of the UAV downwash field. Compared with the no-wind situation, the UAV downwash field also increased the total deposition of all collection points by 4.76%. As a result, the proportion of spray deposition at the center nine collection points did not increase much, with values of 74.84%, 72.40%, and 72.73%, respectively, and an average of 73.28%. It can be seen that in the downwash field area, the deposition amount of droplets becomes more and more uniform, and the deposition amount of droplets in the UAV downwash field will be improved.

Secondly, according to Figure 20a,b, which demonstrates the spray deposition at various collection points under the presence and absence of the downwash field, the deposition amounts in the downwash field area with different downwash airflow velocity are also different. In the Materials and Methods section, this paper establishes the sampling method and positions for the spray volume, which can be specifically seen in Figure 12. The downwash airflow velocity, similar to Figure 19, is extracted from the simulation calculations as the cross-sectional wind field range. The deposition amount of the collection points in the 2 m/s wind field area is 9 mL, 7.67 mL, 7.17 mL, and 7.67 mL, respectively, while the deposition amount of the collection points in the 1 m/s wind field area is 4.83 mL, 4.5 mL, 4.33 mL, and 4.33 mL, respectively. It is worth noting that the central collection point has the highest deposition except in the downwash airflow velocity region of 1 m/s. This is because the central collection point is in the center of four nozzles and is affected by four nozzles at the same time. Observing the collection points in the 2 m/s and 1 m/s wind field areas, it can be seen that the collection points in the 2 m/s wind field area are affected by two nozzles at the same time, and the collection points in the 1 m/s wind field area are greatly affected by one nozzle. This raises a new question: is it because of the influence of downwash airflow velocity or the influence of the location of the collection points that the deposition of droplets in the 2 m/s wind field region is greater than that in the 1 m/s wind field region?

To find the answer to this question, this study increases the rotor speed of the UAV and makes a more powerful UAV downwash field to conduct the same experiment. As shown in Figure 21, under the UAV downwash field with a speed of 5418 rpm, the deposition of droplets is more concentrated in the downwash field area. In the repeated experiments, the total deposition volume of all the collection points was 84.7 mL, 84.2 mL, and 85.9 mL, respectively, and the average was 84.93 mL, which was 6.5% and 1.7% higher than that of the no-wind and 2000 rpm downwash fields, respectively. The total deposition volume of the center nine collection points was 72 mL, 70 mL, and 73 mL, respectively, with an average of 71.67 mL, which was 24.64% and 17.17% higher than that of the center nine collection

points with no-wind and 2000 rpm downwash fields, respectively. The deposition amount of the center nine collection points accounted for 84.38% of the total deposition amount, which was 12.22% and 11.1% higher than that of the no-wind and 2000 rpm downwash fields, respectively. It can be seen that compared with the UAV downwash field of 2000 rpm, the UAV downwash field of 5418 rpm can better illustrate that the deposition of droplets in the UAV downwash field is greater than that in the case without a downwash field.

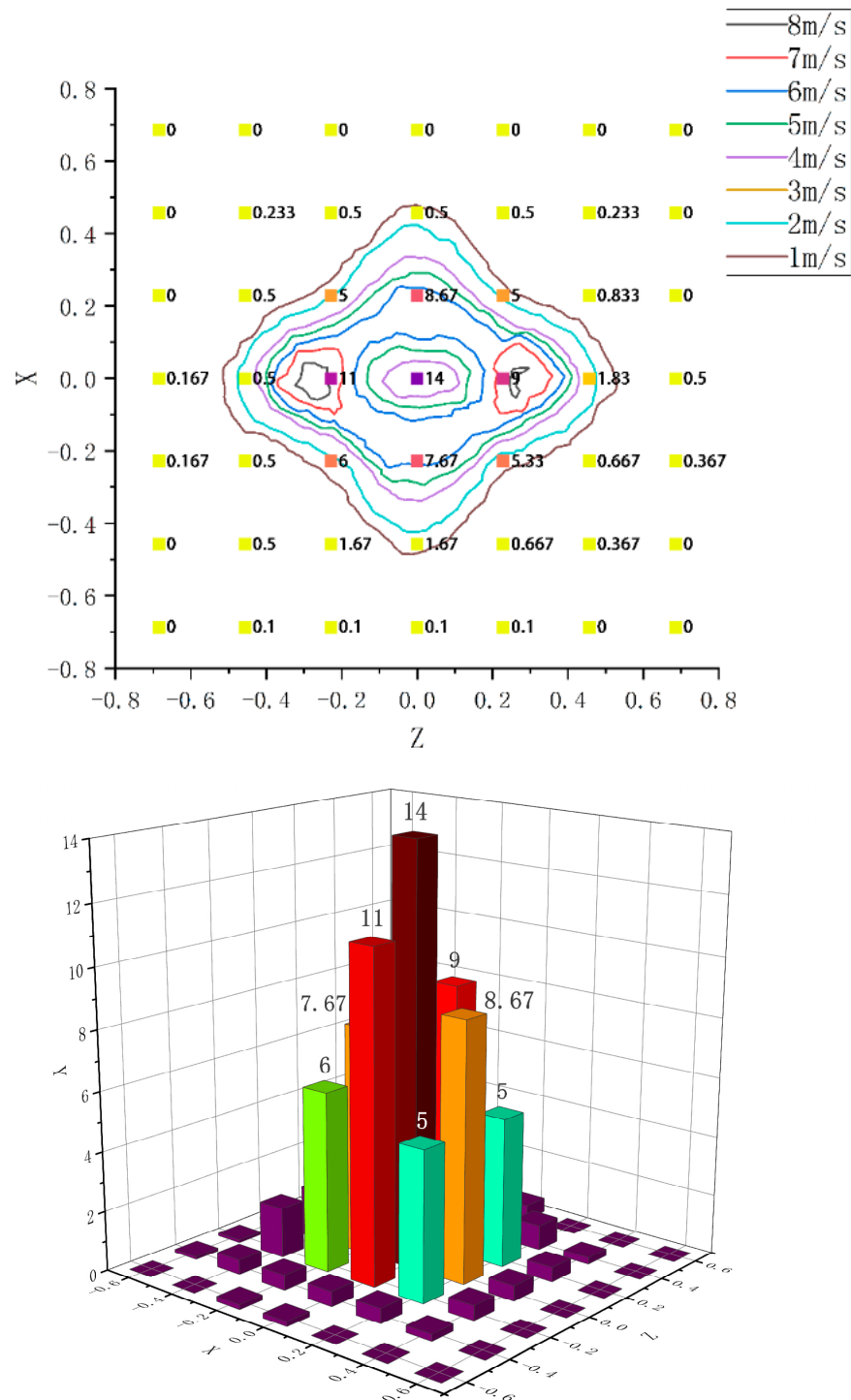


Figure 21. The relationship between the spray deposition volume at various collection points and the 5418 rpm downwash field.

Points 34, 64, 43, and 45 (as shown in Figure 12) were all affected by two nozzles at the same time, but points 34 and 64 had higher spray deposition than points 43 and 45. It can be seen that points 34 and 64 are at the edge of the 8 m/s wind field region, while points 43 and 45 are within the 6 m/s wind field region. It can be concluded that while the collection points are affected by the same number of nozzles, the deposition of droplets (that is, spray deposition volume) in the high downwash airflow velocity wind field region is higher than that in the slightly lower downwash airflow velocity wind field region.

However, wind field regions with different downwash airflow velocities are not the only factor that affects the deposition of droplets. Observing Figure 21, it can be seen that point 24, point 42, point 46, point 64, point 33, point 35, point 53, and point 55 are all within the 2 m/s wind field region at the same time. However, points 24, 42, 46, and 64 do not have the same high deposition as points 33, 35, 53, and 55 (the collection point numbers are shown in Figure 12). This is because the nozzle is positioned directly under the UAV rotor, right above points 33, 35, 53, and 55. They are closer to the nozzle than other points, so they get more droplets deposited. Therefore, even in the same downwash airflow velocity wind field region, the deposition of droplets is still affected by the position of the nozzle.

To sum up, in the UAV downwash field area, the amount of droplets deposited will become higher. Under the same nozzle position, the higher the downwash airflow velocity, the more droplets will be deposited in the downwash field area.

5. Conclusions

In this paper, to address the systematic errors caused by quality issues in different anemometers, a downwash field range test device is designed, and the movement state of the ESP balls under the UAV wind field is used to visualize the boundary of the UAV downwash field. At the same time, the characteristics of multiple wind-field sampling points are collected to verify the accuracy of the simulation calculation, and the maximum error between simulation data and experimental data is less than 10%.

By analyzing the experimental data, the overall downwash field in the vertical plane of the UAV rotor and the vertical plane below the non-UAV rotor shows an expansion trend. Based on the further analysis of the simulation results of the UAV downwash field, the overall shape of the quadrotor downwash field in the expansion is presented as “four-point type–square-like–ellipse-like”, and the distribution area and three-dimensional distribution characteristics of the 1–5 m/s downwash airflow velocity regions at different heights are discussed. After a distance of 0.6 m from the UAV, the downwash field gradually evolves into an “elliptical” shape, with downwash airflow velocity within the wind field being less than 2 m/s. Finally, as shown in Figure 19, the figure illustrates the spatial distribution of different downwash airflow velocity values within the downwash field. It can be seen that only 1 m/s downwash airflow velocity exists at a distance of 1.8 m to 2 m from the UAV.

Through the experiment on the relationship between the range of the downwash field and the deposition of droplets, it is found that more droplets are deposited in the UAV wind field than in the case of no wind. At the same time, it is found that the deposition of droplets is affected by the position of the nozzle and the region of different downwash airflow velocities. Under the same influence of the position of the nozzle, the deposition of droplets in the high downwash airflow velocity region is higher than that in the low downwash airflow velocity region. At the same time, the presence of a high downwash airflow velocity region in the downwash field will cause a large difference between the deposition amount of droplets in the region and the deposition amount of droplets in the low downwash airflow velocity region, resulting in the uneven deposition of droplets. Balancing the position of the nozzle and the different downwash airflow velocity regions of the downwash field can achieve a better spray deposition effect.

In conclusion, this paper has established the relationship between different downwash airflow velocity regions of UAV downwash fields and spray deposition through experiments and CFD simulations. Additionally, the area and boundaries of the UAV downwash

field obtained from simulations provide a direct theoretical basis for the establishment of UAV downwash field models in subsequent studies.

The research objectives for the future of this research can be divided into two aspects. On the one hand, the authors will explore whether the conclusions drawn in this paper are equally applicable to UAVs of different configurations and in different motion states, investigating the universality of the conclusions. On the other hand, the authors will establish a downwash field boundary model through data fitting and other methods, which will be applied to actual agricultural production.

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Appendix A

To enhance the readability of this paper, explanations are provided for some of the terms used in the text.

DJIF450: It is a quadcopter drone with a wheelbase of 450mm, produced by DJI (Shenzhen, China), a company specializing in drones.

T7+ handheld scanner: produced by TECHLEGO Co., Ltd. from Tianjin, China, the 3D scanner.

EPS ball: It refers to the 7 mm diameter spheres made of EPS (expanded polystyrene foam) used in this paper for visualizing the downwash field of the DJIF450.

Downwash airflow velocity: This refers to the wind speed within the downwash field of the UAV.

Spray deposition volume: This refers to the volume of droplets deposited at the collection points.

Downwash range: This refers to the area enclosed by the boundaries of the downwash field.

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