Design Optimization and Testing of Air Delivery System for Orchard Multi-duct Sprayer (Postprint)

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Abstract

To address the problem of non-uniform airflow distribution within the orchard multi-duct sprayer, which leads to turbulent airflow from the outlets and affects the uniform deposition of droplets on fruit tree canopies, the length parameters of the internal deflector plates were optimized. Computational Fluid Dynamics (CFD) technology was applied to simulate and analyze the airflow inside the sprayer' s air supply system using Star-CCM+ software. The standard deviations of wind speed at outlets 1-6 under different deflector plate lengths were obtained as 0.7468, 0.6776, 1.4441, 5.1305, 4.5768, and 0.8209, respectively. Response surface analysis was performed on outlets 3, 4, and 5, which exhibited larger wind speed standard deviations, and the optimal parameter combination was ultimately determined as: deflector plate 1 length of 200.00 mm, deflector plate 2 length of 60.00 mm, and deflector plate 3 length of 50.00 mm. Under this optimal parameter combination, the calculated wind speed values at the symmetric outlets 3 and 6 were 39.135 and 41.320 m/s, respectively, with a relative deviation of 5.58%; the wind speed values at outlets 4 and 5 were 33.022 and 34.328 m/s, respectively, with a relative deviation of 3.95%, meeting the design requirements. Indoor wind speed test results indicated that at a distance of 1.25 m from the sprayer outlets, the wind field velocity increased gradually from the upper layer to the lower layer, achieving a wind field distribution conforming to the shape of the fruit tree canopy. The wind field on the left and right sides of the sprayer was symmetrically distributed with uniform airflow. The design of the orchard multi-duct sprayer satisfies the requirements and can provide a reference for similar designs.

Full Text

Design Optimization and Test of Air Supply System for Multi-Duct Orchard Sprayer

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Abstract: To address the problem of uneven airflow distribution inside multi-duct orchard sprayers, which leads to turbulent airflow at the outlets and affects uniform droplet deposition on fruit tree canopies, this study optimized the length parameters of internal deflector plates. Computational Fluid Dynamics (CFD) technology was employed to simulate and analyze the internal airflow of the sprayer' s air supply system using Star-CCM+ software. The standard deviations of wind speed at outlets 1-6 under different deflector plate lengths were 0.7468, 0.6776, 1.4441, 5.1305, 4.5768, and 0.8209 m/s, respectively. The standard deviations at monitoring points 1, 2, and 6 were all less than 1, indicating that deflector plate length variations had negligible impact on wind speed at outlets 1, 2, and 6. In contrast, the larger standard deviations at points 3, 4, and 5 showed that wind speeds at outlets 3, 4, and 5 were significantly affected by deflector length changes. Based on this, response surface analysis was conducted for outlets 3, 4, and 5, ultimately determining the optimal parameter combination: deflector plate 1 length of 200.00 mm, deflector plate 2 length of 60.00 mm, and deflector plate 3 length of 50.00 mm. Under these optimal parameters, the wind speeds at symmetric outlets 3 and 6 were 39.135 m/s and 41.320 m/s, respectively, with a relative deviation of 5.58%. The wind speeds at outlets 4 and 5 were 33.022 m/s and 34.328 m/s, respectively, with a relative deviation of 3.95%, meeting the sprayer' s design requirements. Indoor wind speed tests demonstrated that at 1.25 m from the sprayer outlets, the wind field speed increased progressively from the upper to lower layers, achieving a canopy-shaped distribution. The wind fields on both sides of the sprayer were symmetrically distributed with uniform airflow, satisfying design specifications and providing a reference for similar designs.

Keywords: Computational Fluid Dynamics (CFD); multi-duct sprayer; air supply system; flow field simulation; response surface methodology; uniform deposition

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1 Introduction

Orchard spraying operations involve complex processes influenced by numerous factors, including pesticide dosage and spray volume, droplet distribution, air volume, airflow patterns, sprayer speed, meteorological conditions, and crop characteristics [**?**]. These operations must maximize biological efficacy while minimizing residues and balancing environmental impact [?, ?]. Given the multitude of sprayer and environmental parameters, experimental analysis alone is difficult and costly [?], making the combination of simulation and experimentation an effective approach. Computational Fluid Dynamics (CFD) technology has been extensively applied to help solve these complex processes.

Researchers have widely applied CFD technology to air-assisted sprayer design. Wang et al. [?] conducted numerical analysis of an axial flow fan, finding that pressure loss was minimized when inlet velocity ranged from 25-55 m/s with diffusion angles of 4.5° or 5.5°, though pressure loss increased with rising inlet velocity. Qiu et al. [?] designed a self-propelled orchard directional air-blowing sprayer, completing structural design and key component parameter determination through theoretical design and virtual prototyping, with performance verified through field tests. Zhou et al. [?] designed a combined disc-type orchard air-assisted sprayer and determined optimal operating parameters through field experiments. Chen [?] utilized CFD technology to analyze the airflow field in a centrifugal fan outlet chamber, demonstrating that installing rounded guide blocks in the fan chamber could increase airflow by 0.27%-3.69%. Ding et al. [?] addressed uneven airflow distribution in single-fan channel orchard sprayers using CFD numerical simulation to compare airflow fields between single and double-channel designs. Endalew et al. [?] developed a CFD-based orchard air-assisted model that directly captured canopy shape and its local effects on natural and spray airflow, yielding more realistic results. Nuyttens et al. [?] established a 3D spray drift model for sprayers using CFD technology, combining canopy and environmental factors for airflow simulation analysis. Badules et al. [?] developed a CFD model to study the effects of sprayer operating speed on crossflow air-assisted sprayer external 3D airflow. Hong et al. [?] developed an integrated CFD model to predict airflow velocity distribution within and around tree canopies from air-assisted sprayers, employing sliding mesh technology to simulate sprayer movement and defining tree canopies as virtual porous media in the computational domain. Zheng et al. [?] used CFD technology to simulate external airflow fields of sprayers, validating results under laboratory conditions. Holownicki et al. [?] developed an integrated CFD model to predict airflow velocity distribution within and around tree canopies, using sliding mesh technology for nozzle movement simulation and defining canopy models as virtual porous media, with validation through comparison with previous measurements. Zhai et al. [?] applied CFD fluid simulation technology to model and test the outlet airflow field of tower sprayers, investigating turbulence model and computational domain size effects on wind field distribution results.

Previous CFD studies on various sprayer types revealed that model construction directly affects wind field outcomes. Unreasonable internal guide structure arrangement in multi-duct air-assisted sprayers directly causes uneven outlet wind speed distribution. To optimize the internal air duct design of orchard multi-duct sprayers and obtain optimal deflector plate parameters, this study applied CFD technology based on Star-CCM+ software to simulate internal airflow in the sprayer’ s air supply system. Numerical simulation analysis was used to study airflow distribution patterns within the air supply system, with simplified models simulated under various parameters. The internal flow field and outlet wind speeds were observed to ultimately determine the optimal deflector plate length inside the air duct, achieving symmetrical airflow distribution from both sides of the sprayer.

2.1 Air Duct Design

The multi-duct outlet device is a key component connecting the turbo centrifugal fan, distributing airflow generated by the fan to various outlet channels. Traditional air-assisted orchard sprayers typically use axial or centrifugal fans to generate required airflow, with deflector devices (such as guide plates) altering airflow field distribution. These devices feature large outlet areas, causing semi-circular diffusion airflow patterns where some fan-generated airflow cannot effectively reach target areas, resulting in airflow loss and reduced outlet wind speeds. This study designed a multi-duct outlet device composed of multiple internal channels with identical cross-sections, ensuring precise and effective airflow direction toward target locations. Based on preliminary fruit canopy measurement data, duct distribution was calculated by approximating the canopy as a conical shape and dividing it into layers. The upper, middle, and lower canopy radii were 0.40 m, 0.80 m, and 1.10 m, respectively, with canopy volumes calculated using formula (1):

$$V = \frac{\pi h}{3}(R^2 + r^2 + Rr)$$

where V represents canopy volume (m^3), h represents height difference between upper, middle, and lower layers (m, taken as $h = 1.00$ m based on tree height of approximately 3.50 m with lateral branches beginning at 0.50 m above ground, leaving 3.00 m divided equally into three layers), R represents lower base radius (m), and r represents upper base radius (m).

Calculated canopy volumes for lower, middle, and upper layers were 2.8 m^3, 1.1 m^3, and 0.3 m^3, respectively. During outlet design, the two lower outlets needed to cover half the circular arc surface, with middle and upper outlets extending upward from the arc surface divided into four equal portions. Three internal deflector plates controlled airflow volume, with lengths from left to right determined through internal airflow simulation analysis in Section 3 as 200.00 mm, 60.00 mm, and 50.00 mm [Figure 1: see original paper]. To avoid turbulence at large turns during internal duct design, universal guide vanes were installed to ensure smooth airflow passage and minimize velocity loss.

Based on relevant data and field investigations of the Hebei Lüyang Modern Agricultural Park in Quyang County, Baoding City, Hebei Province (38°N, 114°E), where apple orchard row spacing was 3.50 m, the optimal spraying distance was determined to be 1.25 m [?]. Combining agricultural machinery and agronomic practices, the overall dimensions of the multi-duct sprayer' s air duct section were designed as 1.00 m wide and 2.00 m high. Three-dimensional modeling was performed using AIP (Autodesk Inventor Professional) software, yielding the structural diagram of the main duct section [Figure 1: see original paper].

2.2 Outlet Design

The orchard multi-duct sprayer utilizes high-speed airflow from the fan for secondary droplet atomization, enabling full droplet-target contact. Therefore, fan-generated airflow should fully interact with droplets. Since circular duct outlets produce linear airflow without jet diffusion, a duckbill-type combined nozzle outlet was designed based on the spray diagram shown in [Figure 2: see original paper]. The outlet measures 360 mm in length, 45 mm in width, with a fan diffusion angle of 55.0° to achieve canopy-wide coverage. The design includes an inlet, duckbill-type outlet, spray pipe, nozzle, fixing plates, and other components, with the structural block diagram shown in [Figure 3: see original paper].

In this design, the transition from rectangular cross-section internal ducts to circular cross-section delivery channels, then to duckbill-type outlets, effectively increases air pressure and expands spray width. This allows nozzle droplets to fully contact with duckbill outlet airflow while maintaining uniform distribution [?], with obvious secondary atomization effects. Airflow carries droplets to uniformly spray target areas while flipping leaves to ensure uniform medication deposition on both leaf surfaces.

3.1 Factor Analysis

In the orchard multi-duct air-assisted sprayer, the internal ducts of the upper and middle outlets are divided by three deflector plates of different lengths. These plates regulate high-speed airflow from the centrifugal fan to control airflow field distribution within the sprayer' s internal air supply system [Figure 1: see original paper]. The high-speed airflow generated by the centrifugal fan is directionally transported to each outlet under the guidance of the sprayer' s ductwork, with the guiding process significantly affecting operational performance. Different deflector plate lengths influence internal airflow distribution, producing varying spray effects and impacting operational efficiency.

Analysis identified the primary influencing factors as the lengths of the three deflector plates. Deflector plate 1 length directly affects wind speed and volume at outlets 3, 4, and 5, while deflector plates 2 and 3 guide airflow at these outlets

[Figure 1: see original paper]. To determine the optimal combination, a three-factor, three-level experimental design was established. Deflector plate lengths had to meet system airflow requirements, with the lower limit determined by the required airflow volume of 3.61 m^3/s. Following a sequential decreasing pattern, initial deflector plate lengths were designed as: deflector plate 1 length $L_1 =$ 225.00 mm, deflector plate 2 length $L_2 =$ 85.00 mm, and deflector plate 3 length $L_3 =$ 65.00 mm . Regression experiments were designed using Design-Expert software, with the experimental scheme shown in .

3.2 Model Establishment and Simulation Testing

The sprayer model was initially built using AIP software, with deflector plate lengths modified according to experimental requirements. Thirteen sets of fluid domain models were sequentially imported into Star-CCM+ software for surface repair, Boolean operations, boundary condition setting, physical model definition, mesh generation, and post-processing analysis, with wind speeds monitored at six outlets. The multi-duct sprayer fluid domain model [Figure 4: see original paper] employed polyhedral meshes with local refinement at interfaces and fan walls. After model setup, monitoring points were established at each outlet [Figure 4: see original paper], with velocity monitoring reports created based on these points to obtain average airflow velocity calculations. A middle cross-section was selected to observe velocity vector distributions in post-processing.

4.1 Internal Flow Field Simulation Analysis Based on Star-CCM+

After simulation completion, velocity monitoring reports for each monitoring point and velocity vector diagrams for each model cross-section were exported from Star-CCM+ software [Figure 5: see original paper]. Simulation results were compiled and analyzed, clearly showing internal airflow changes in the duct. Monitoring point velocity reports were organized and analyzed [Figure 6: see original paper]. For monitoring points 1-6 in sequence, wind speed standard deviations under different deflector plate lengths were 0.7468, 0.6776, 1.4441, 5.1305, 4.5768, and 0.8209 m/s. Points 1, 2, and 6 showed standard deviations less than 1, indicating minimal impact of deflector length variations on wind speed at outlets 1, 2, and 6. In contrast, points 3, 4, and 5 exhibited larger standard deviations, demonstrating that wind speeds at outlets 3, 4, and 5 were significantly affected by deflector length changes.

4.2 Results Analysis and Verification

To obtain optimal deflector plate length parameters, Response Surface Methodology (RSM) was applied to further investigate average simulated wind speed values at points 3, 4, and 5. The wind speed response values at these three points were designated as Y_3, Y_4, and Y_5, with influencing factors deflector plate 1 length as A, deflector plate 2 length as B, and deflector plate 3 length as C. Regression analysis was performed to derive regression equations.

4.2.1 Outlet 3

Analysis of average simulated wind speed values at outlet 3 yielded the regression equation:

$$Y_3 = 39.13 - 1.07 \times A - 0.13 \times B - 0.17 \times C + 0.13 \times AB + 0.19 \times AC + 0.16 \times BC - 1.84 \times A^2 - 1.34 \times B^2 - 0.58 \times C^2 \tag{2}$$

Significance and variance analysis of the regression equation are presented in . The model P-value < 0.01 indicates extreme significance, with a determination coefficient $R^2 = 0.9979$, demonstrating good model fit for analysis and prediction. First-order terms A, B, and C were highly significant; interaction terms AB, AC, and BC were significant; quadratic terms A^2, B^2, and C^2 were highly significant. The average wind speed value Y_3 at outlet 3 served as the evaluation criterion and optimization objective, with the goal of maximizing Y_3 under constraints of deflector plate 1, 2, and 3 lengths, expressed as:

$$\max\text{: } Y_3 = f(A, B, C) \tag{3}$$

To verify reliability, three parallel simulation tests were conducted using optimal deflector parameters, yielding outlet 3 average wind speeds of 38.789, 39.420, and 38.517 m/s, with a mean of 38.909 m/s. This result closely matched the predicted value with a relative error of 0.58%, confirming the model' s accurate predictive capability.

Response surface results for outlet 3 average wind speed [Figure 7: see original paper] clearly show interactions between deflector plates 1, 2, and 3, with significant wind speed changes under combined factor effects. Analysis within the experimental factor ranges determined the optimal deflector plate combination as: deflector plate 1 length 200.00 mm, deflector plate 2 length 60.00 mm, and deflector plate 3 length 50.00 mm, achieving an outlet 3 average wind speed of 39.135 m/s.

4.2.2 Outlet 4

Analysis of average simulated wind speed values at outlet 4 produced the regression equation:

$$Y_4 = 33.02{+}4.04{\times}A{-}4.37{\times}B{-}1.31{\times}C{-}2.24{\times}AB{+}3.78{\times}AC{+}1.72{\times}BC{+}3.10{\times}A^2{-}2.21{\times}B^2{-}2.28{\times}C^2 \tag{4}$$

Significance and variance analysis are shown in . The model P-value < 0.01 indicates extreme significance, with $R^2 = 0.9704$, showing good fit. First-order terms A and B were highly significant, C significant; interaction AC highly significant, AB and BC significant; quadratic term A^2 highly significant, B^2 and C^2 significant. The average wind speed Y_4 at outlet 4 served as the optimization objective:

$$\text{max: } Y_4 = f(A, B, C) \tag{5}$$

Three parallel simulation tests using optimal parameters yielded outlet 4 average wind speeds of 43.215, 43.269, and 43.478 m/s, with a mean of 43.321 m/s, showing a relative error of 0.02% compared to predicted values and confirming model accuracy.

Response surface analysis [Figure 8: see original paper] revealed significant interactions between all deflector plates. Within experimental ranges, the optimal combination was deflector plate 1 length 223.72 mm, deflector plate 2 length 41.09 mm, and deflector plate 3 length 50.21 mm, achieving an outlet 4 average wind speed of 43.310 m/s.

4.2.3 Outlet 5

Analysis of average simulated wind speed values at outlet 5 generated the regression equation:

$$Y_5 = 34.33{-}4.71{\times}A{+}3.54{\times}B{-}0.87{\times}C{+}3.82{\times}AB{+}0.88{\times}AC{+}0.87{\times}BC{-}0.70{\times}A^2{-}1.69{\times}B^2{+}0.69{\times}C^2 \tag{6}$$

Significance and variance analysis results are listed in . The model P-value $<$ 0.01 indicates extreme significance, with $R^2 = 0.9946$, demonstrating excellent fit. First-order terms A, B, and C were highly significant; interactions AB, AC, and BC significant; quadratic term B^2 highly significant, A^2 and C^2 significant. The average wind speed Y_5 at outlet 5 served as the optimization objective:

$$\text{max: } Y_5 = f(A, B, C) \tag{7}$$

Three parallel simulation tests using optimal parameters produced outlet 5 average wind speeds of 40.129, 41.246, and 41.875 m/s, with a mean of 41.083 m/s, showing a relative error of 0.29% and confirming reliable prediction.

Response surface results [Figure 9: see original paper] showed significant interactions between deflector plates. Within experimental ranges, the optimal combination was deflector plate 1 length 175.00 mm, deflector plate 2 length 51.53 mm, and deflector plate 3 length 35.00 mm, achieving an outlet 5 average wind speed of 40.963 m/s.

4.2.4 Comprehensive Analysis

Since outlets 4 and 5, and outlets 3 and 6 are symmetrically positioned, uniform airflow requires symmetrical distribution. To minimize error and ensure data processing reliability, relative error analysis was performed on symmetric outlet wind speeds for three parameter combinations . The analysis confirmed deflector plate 1 length 200.00 mm, deflector plate 2 length 60.00 mm, and deflector plate 3 length 50.00 mm as the optimal parameter combination.

The wind field wind speed increased progressively from upper to lower layers, achieving canopy-shaped distribution. According to Dai's end-velocity principle [**?**], airflow velocity reaching the tree interior should reach 9–10 m/s. Indoor wind speed experiments showed upper layer average wind speed of 15.750 m/s, middle layer 20.830 m/s, and lower layer 28.270 m/s, satisfying the end-velocity principle while verifying uniform, symmetrical wind field distribution on both sprayer sides.

5.1 Test Protocol

To investigate wind field distribution of the orchard multi-duct sprayer air supply system and verify simulation optimization accuracy, indoor wind speed tests were conducted using the optimized spray parameters.

Test equipment included the multi-duct sprayer air supply system, anemometer (AS856S, Xima Company), measuring poles, tape measure, three-phase asynchronous motor (Y2-90L-2 pole), and frequency converter (M2-2R2G3). The first monitoring point was established at 0.50 m above ground on the measuring pole, with additional points marked every 0.30 m up to 3.50 m. The frequency converter was connected to the motor and three-phase power supply. The pole was positioned 1.25 m from the sprayer outlet axis. Power was activated, and frequency was gradually increased to 39 Hz, producing a fan speed of 2184 r/min. After stabilization, the anemometer measured wind speeds at each point. Measurements were repeated on the opposite side, with three parallel tests per side.

5.2 Validation Results Analysis

Recorded wind speed values from both sprayer sides were processed using data analysis software, producing the point-line diagram shown in [Figure 10: see original paper]. At 1.25 m from outlets, the wind field distribution demonstrated progressively increasing wind speeds from upper to lower layers, achieving canopy-shaped distribution. Test results validated symmetrical wind field distribution on both sprayer sides.

6 Conclusions

This study addressed uneven airflow distribution in multi-duct sprayers that caused turbulent outlet airflow and non-uniform droplet deposition on fruit tree canopies. Using Star-CCM+ software for internal airflow field simulation and response surface analysis, optimal deflector plate lengths were determined and validated through indoor wind speed tests.

1. CFD technology based on Star-CCM+ software simulated internal airflow in the orchard multi-duct sprayer air supply system, yielding wind speed standard deviations at outlets 1-6 of 0.7468, 0.6776, 1.4441, 5.1305, 4.5768, and 0.8209 m/s under different deflector lengths.

2. Response surface analysis of outlets 3-5 (with larger standard deviations) determined the optimal parameter combination: deflector plate 1 length 200.00 mm, deflector plate 2 length 60.00 mm, and deflector plate 3 length 50.00 mm. Under these parameters, symmetric outlets 3 and 6 achieved wind speeds of 39.135 m/s and 41.320 m/s (relative deviation 5.58%), while outlets 4 and 5 reached 33.022 m/s and 34.328 m/s (relative deviation 3.95%), meeting design requirements.

3. Indoor wind speed tests confirmed that at 1.25 m from sprayer outlets, wind field speed increased from upper to lower layers, achieving canopy-shaped distribution with symmetrical, uniform wind fields on both sides.

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