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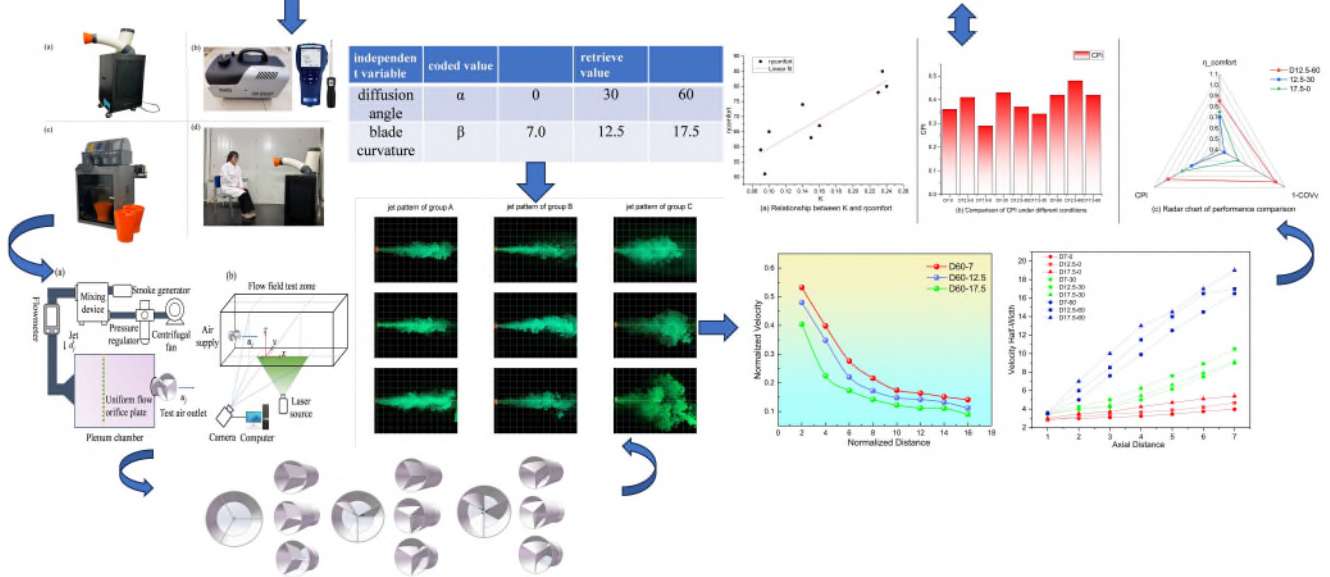
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Graphics Abstract:

Investigation on Geometric Parameter Effects of Swirl Diffusers on Jet Characteristics and Thermal Comfort Performance in Portable Air Conditioning Systems



Case	Key Advantage	Recommended Application Scenario
D17.5-60	Balanced airflow throw and thermal comfort	Scenarios with a slightly distant target zone (2.2–2.5 m) and high comfort requirements (η comfort > 80%).
D7-60	Compact structure	Compact devices with strict limits on outlet area, while still requiring strong mixing and high thermal comfort.



Abstract:
This study investigates the velocity decay of supply air jets in air-conditioning systems, focusing

on swirl diffusers. Through experiments and performance metrics, it examines how geometric parameters affect jet behavior and thermal comfort. Experiments were conducted in a temperature-controlled chamber (35.0 ± 0.5 °C) using nine diffuser configurations with varying diffusion angles ($\alpha = 7.0^\circ, 12.5^\circ, 17.5^\circ$) and blade curvatures ($\beta = 0^\circ, 30^\circ, 60^\circ$). A hot-wire anemometer array was used to measure axial velocity decay, radial dispersion, and velocity distribution. Based on ASHRAE Standard 55, key indices—including velocity uniformity (COV_v) and comfort compliance rate (η_{comfort}) were evaluated, and a composite performance index (CPI) was developed. Results show that blade curvature (β) is the dominant factor. Swirl ($\beta > 0^\circ$) generates a central recirculation zone, enhancing mixing and shifting the flow from transport-dominated to mixing-dominated. The effect of diffusion angle (α) is non-monotonic, with $\alpha = 12.5^\circ$ providing the best balance.

The configuration D12.5–60 performs best, while the conventional straight diffuser D17.5–0 performs worst ($\text{CPI} = 0.331$). The study establishes a clear link between geometry, flow structure, and thermal comfort, offering practical guidance for diffuser design.

Keywords: portable air conditioning; swirl jets; swirl diffusers; geometric parameters; airflow organization; thermal comfort.

1 Introduction

Humans spend their lives working across diverse environments, where thermal conditions constitute a critical factor influencing both comfort and health^[1]. Once basic physiological needs are met, thermal comfort emerges as a vital indicator of environmental quality in modern workplaces. Research demonstrates that the growing prevalence of flexible work arrangements, telecommuting^[2], and remote collaboration has given rise to markedly personalized and localized perceptions of indoor thermal environments^[3]. Lipczynska A^[4] found that in typical office settings, the proportion of occupants dissatisfied with thermal conditions routinely exceeds 20%. M. Luo^[5] explored how vast individual differences in physiology, psychology, activity levels, and clothing render uniform environmental settings inadequate for meeting universal thermal comfort requirements. This “thermal comfort war” not only undermines employee productivity and wellbeing but also drives enormous energy waste. Addressing this, K Jiang^[6] presciently identified efficient local control of the microenvironments immediately surrounding occupants.

Portable air conditioners (PACs) combine market potential with inherent advantages, representing a promising new direction for HVAC energy efficiency^[7] and comfort advancement. G. Parkhurst^[8] reviewed the surging adoption of portable air conditioners across Europe in recent years, characterizing the growth as both rapid and profound. T. Beran^[9] experimentally validated research on patented portable air conditioning technologies. Liu Juan^[10] undertook intelligent, low-noise, energy-efficient portable air conditioner design, while the legitimacy of their existence has been further corroborated by Zhang Y^[11] scenario analysis of hydrofluorocarbon emission reduction in China’s portable air conditioning industry, which identified broader macro-trends. Comparative analyses of energy efficiency across different air conditioning types reveal that PACs typically exhibit lower energy efficiency ratios^[12]. The core issue lies in structural and operational constraints: PAC air outlet designs^[13] often fail to adequately optimize airflow organization, resulting in severe cooling capacity losses during transmission and difficulty efficiently and precisely reaching human activity zones. Empirical research has revealed^[14] that under identical cooling loads; PACs’ seasonal energy efficiency ratios (SEER) may fall more than 25% below split-type units of equivalent cooling capacity—a discrepancy that undoubtedly exacerbates building energy consumption and significantly deviates from energy conservation and emission reduction objectives.

Constrained by their structure and operating principles, PAC air outlet designs^[15] often insufficiently optimize airflow organization, leading to severe cooling capacity transmission losses and difficulty efficiently and accurately reaching human activity zones. In recent years, airflow organization optimization for PACs in such specific application scenarios, particularly the fluid dynamics^[16] design of their core component, the air outlet diffuser—has remained underdeveloped. Current diffuser designs predominantly emphasize aesthetics or universality, while mechanistic research on internal flow field characteristics, jet entrainment effects^[17], and precise matching with indoor thermal load distributions remains inadequate, constituting a gap this study aims to fill. Therefore, this research endeavors to achieve significant improvements in cooling capacity transmission efficiency through refined fluid dynamics optimization design of PAC air outlet diffusers.

Wang’s^[18] review clearly demonstrates that by optimizing air outlet geometry, one can

actively regulate jet entrainment, throw distance, and coverage area, thereby achieving optimal cooling capacity transport. Chen JK [19] experimentally investigated the influence of different air outlet geometries on jet diffusion and entrainment characteristics. Exss K^[20] developed a personalized air outlet with rotating grilles, effectively improving breathing zone air quality and reducing draft sensation through dynamically varying airflow. Yang^[21] contend that direct air conditioning flow toward human bodies causes discomfort, their research aiming to develop a novel ventilation outlet for public air conditioning exits within socket connectors. Concurrently, Chen W^[22] also proposed in research on fan air conditioner thermal comfort, to some extent altering parameters such as outlet geometry. Therefore, research on personalized air outlets oriented toward user health and comfort, exploring personalized ventilation patterns, holds significant engineering application value and practical significance. Current research seldom addresses the impact of geometric parameter variations in portable air conditioner swirl diffusion outlets on airflow distribution.

To address these gaps, targeting the low energy efficiency and unreasonable airflow organization prevalent in current portable air conditioner applications, this study establishes an experimental research platform focusing on air outlet diffusers as the core research object, conducting systematic analysis of airflow organization characteristics. By varying air outlet structural parameters and operating conditions, this research investigates airflow diffusion patterns, entrainment effects, and velocity decay characteristics in indoor environments, analyzing their impact mechanisms on cooling capacity transport efficiency. Building upon this foundation, combined with human thermal comfort requirements, comprehensive evaluation of air supply performance under different operating conditions is conducted. Research findings can provide theoretical support and engineering reference for PAC air supply structure optimization and efficient personalized environmental control.

2 Experimental Methods

2.1 Experimental subject

To authentically simulate the high-temperature environment of non-air-conditioned industrial workshops during summer, experiments were conducted in an environmental simulation laboratory at a university in Liaoning Province, China. The climate chamber measures 5.0 m (length) $\times$ 4.0 m (width) $\times$ 3.0 m (height), As illustrated in Figure 1(d), with ambient temperature maintained at $35.0 \pm 0.5^\circ\text{C}$. The laboratory's mean radiant temperature was $28.5 \pm 0.5^\circ\text{C}$, with relative humidity stabilized at $24.3 \pm 0.5\%$ RH. The jet system comprised a portable air conditioner, smoke generator, smoke-mixing apparatus, all interconnected.

As illustrated in Figure 1(a), The localized cooling airflow was provided by an Aucamp portable air conditioner (dimensions: 0.405 m length $\times$ 0.43 m width $\times$ 0.855 m height; cooling capacity: 2700 W; air circulation volume: 450 m³/h; refrigerant: R410; net weight: 40 kg, gross weight: 44 kg), coupled with an external centrifugal fan (XGB1500; power: 1.0 kW; rotational speed: 2800 rpm; air volume: 240 m³/h) for velocity regulation. The air conditioning system delivered cooled air through flexible ducting via outlet diffusers to the test area, with the outlet connected to an anemometer (DATALOGGING 9671) for continuous monitoring of supply

temperature and velocity, ensuring precise experimental parameter. This is a smoke generator for As illustrated in Figure 1(b), On the left is a 1200-type fog machine for flow field visualization; on the right is a handheld multi-parameter measuring instrument for environmental parameter monitoring. control Velocity measurements were performed using a TSI-9535 hot-wire anemometer with accuracy of $\pm 3\%$ (± 0.015 m/s). Velocity distribution variance was approximately 0.8%, with turbulence intensity below 0.25%. Measurement ports for transverse velocities were distributed along the lower wall. Experimental data presented herein represents averages of multiple measurements, with each trial repeated three times to ensure reproducibility, maintaining standard deviation within $\pm 4\%$.

To qualitatively analyze evolutionary characteristics of jet flow structures under different diffuser conditions, this study employed smoke generator-based visualization methodology. A custom smoke-mixing device was installed in the duct system connecting the flow meter and jet outlet. This apparatus effectively mixes smoke with air to enhance smoke stream visibility. The smoke-mixing device connected to a smoke generator (1500 FOGGER) continuously produced substantial smoke volumes, providing high visibility and resolution for direct observation of flow phenomena through green laser slicing. During experiments, different swirl diffusers with varying geometric parameters were replaced to capture corresponding jet development morphologies.

A continuous laser with wavelength 532 nm and power 2 W generated a sheet light source approximately 2 mm thick, illuminating the jet's central cross-section. Smoke followed airflow motion, enabling clear presentation of flow structures. High-resolution cameras continuously photographed the flow field, focusing on capturing typical features including initial jet region breakdown processes, large-scale vortex structure generation and evolution, and jet diffusion boundaries. Experiments were conducted under standard temperature and pressure conditions, defined as pure jet experiments where crossflow and jet possessed identical density and kinematic viscosity.

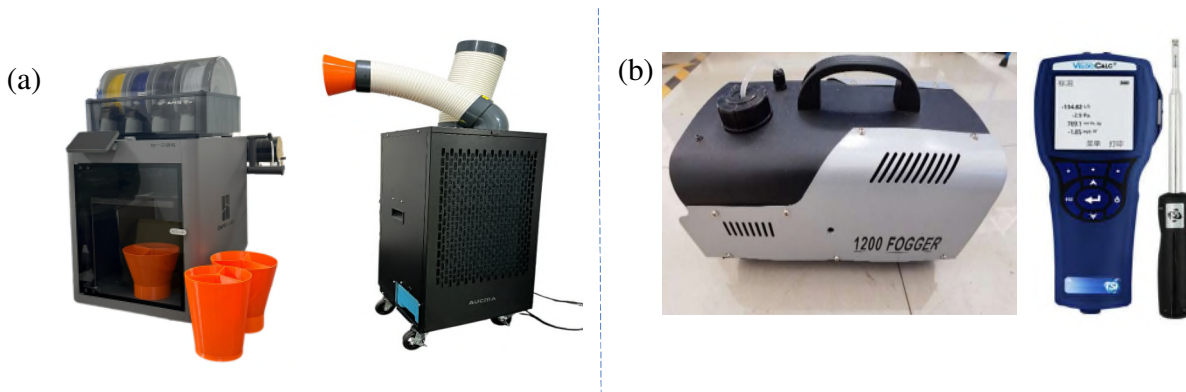


Fig. 1. (a) mobile air conditioner and 3D modeling software; (b) smoke generator and Measurement instruments: TSI-9535 hot-wire anemometer;

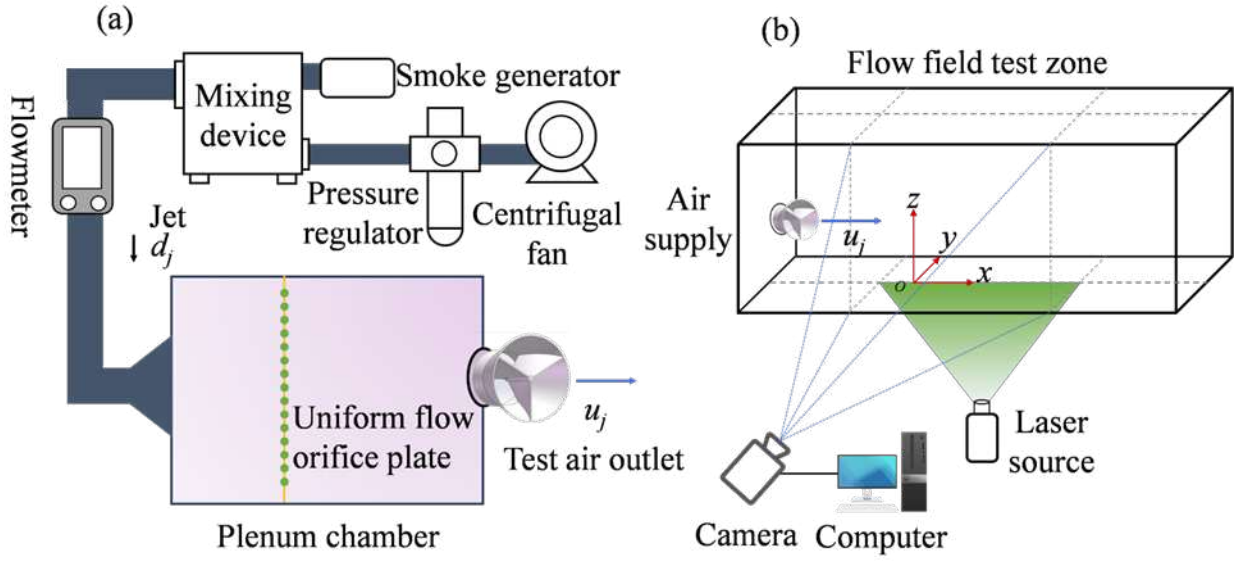


Fig. 2. (a) Diagram of the experimental platform and overall composition of the flow visualization; (b) Connection diagram of

2.4 Experimental process

To acquire spatial distribution characteristics of jet velocity and temperature fields under different configurations, this study employed multi-point measurement methodology based on hot-wire anemometry for quantitative flow field characterization. Local air temperature was recorded for temperature correction of velocity measurements. Through this combined measurement approach, synchronized acquisition of jet velocity and temperature fields was achieved, ensuring comparability and consistency of data across different configurations. To capture velocity and temperature distribution characteristics of jets across spatial domains, this study established a measurement grid based on cylindrical coordinates, where the z -axis aligns with the jet centerline direction, the r -axis represents the radial direction perpendicular to the axis, and the origin is defined at the diffuser outlet center.

In the axial direction (z -axis), measurement cross-sections employed segmented arrangement. The near-field region ($z < 2.0$ m), characterized by intense velocity and temperature variations, utilized smaller measurement plane spacing at $z = 0.2, 0.5, 1.0, 1.5$, and 2.0 m. The far-field region ($z \geq 2.0$ m), where flow gradually stabilizes, employed appropriately increased measurement intervals at $z = 2.5, 3.0, 4.0$, and 5.0 m. At each axial cross-section, measurement points were symmetrically arranged along the radial direction (r -axis) from the centerline ($r = 0$) outward. The near-field region ($z < 2.0$ m) adopted smaller radial step size $\Delta r = 0.05$ m to capture steeper velocity gradients; the far-field region ($z \geq 2.0$ m) employed increased radial step size $\Delta r = 0.10$ m to enhance measurement efficiency while covering larger diffusion ranges. Radial measurement range was dynamically determined based on local velocity decay, extending to positions where axial velocity decreased to 0.2 m/s as boundaries.

Based on this arrangement, a two-dimensional grid (r - z plane) comprising multiple axial cross-sections and radial measurement points was formed, covering the primary development region

from outlet to decay zone. During experiments, a positioning system moved the hot-wire probe point-by-point to preset coordinate locations, completing data acquisition for all measurement points in fixed sequence.

This study aims to investigate the influence of key geometric parameters on jet characteristics. To approximate engineering application scenarios, this research designed and fabricated a series of swirl diffusers, conducting comparative experiments under uniform supply conditions.

This study selected two independent variables: diffusion angle (α) and blade curvature angle (β). Diffusion angle α is defined as the angle between the outer conical diffusion body of the diffuser and the central axis, with three levels: 7.0° , 12.5° , and 17.5° . Blade curvature angle β is defined as the angle between internal guide vanes and the axial direction, characterizing swirl intensity, with three levels: 0° (no swirl), 30° (weak swirl), and 60° (strong swirl). Through combination of these two variables, $3 \times 3 = 9$ experimental configurations were formed. Each configuration is designated using the “D α - β ” nomenclature (e.g., D7.0-30). Additionally, for comparative analysis, a traditional square multi-layer louver grille diffuser was introduced as the baseline configuration, totaling 9 experimental groups.

To systematically investigate the effects of diffusion angle and blade curvature on jet characteristics, the nine diffuser configurations were divided into three groups:

Group A: Non-swirling jet group. This group comprises three diffusers with zero blade curvature ($\beta=0^\circ$): D7-0 ($\alpha=7^\circ$, $\beta=0^\circ$), D12.5-0 ($\alpha=12.5^\circ$, $\beta=0^\circ$), and D17.5-0 ($\alpha=17.5^\circ$, $\beta=0^\circ$). This group serves to establish baseline jet characteristics under non-swirling conditions.

Group B: Moderate swirling jet group. This group contains three diffusers with a fixed blade curvature of $\beta=30^\circ$: D7-30 ($\alpha=7^\circ$, $\beta=30^\circ$), D12.5-30 ($\alpha=12.5^\circ$, $\beta=30^\circ$), and D17.5-30 ($\alpha=17.5^\circ$, $\beta=30^\circ$). Among these, D12.5-30 represents the optimized diffuser configuration of primary interest in this study and will serve as the main research subject in subsequent analyses.

Group C: Strong swirling jet group. This group is designed to explore the limiting mixing characteristics under strong swirl conditions and their potential influence on jet throw. It consists of three diffusers with blade curvature set at $\beta=60^\circ$: D7-60 ($\alpha=7^\circ$, $\beta=60^\circ$), D12.5-60 ($\alpha=12.5^\circ$, $\beta=60^\circ$), and D17.5-60 ($\alpha=17.5^\circ$, $\beta=60^\circ$).

To ensure comparability among different diffuser configurations, this study maintained constant supply volume across all conditions: $Q = 350 \text{ m}^3/\text{h}$. According to the continuity equation, outlet average velocity and outlet area satisfy:

$$Q = V_0 \cdot A_{\text{out}} \quad (1)$$

For circular diffusers, the equivalent diameter is:

$$D_{\text{eq}} = \sqrt{\frac{4A_{\text{out}}}{\pi}} \quad (2)$$

The diffuser expansion section employs an axisymmetric conical structure, guide vanes form swirl by introducing tangential velocity components with radius variation along the axial direction and velocity decomposition relationship expressed as:

$$r(x) = r_0 + x \tan(\alpha) \quad (4)$$

$r(x)$ represents radius at position x , r_0 indicates inlet radius, α is the diffusion angle

$$\tan(\beta) = \frac{V_{\theta}}{V_x} \quad (5)$$

V_{θ} represents tangential velocity, V_x denotes axial velocity, β is the blade curvature angle

As $\tan(\beta)$ increases, swirl intensity strengthens, thereby enhancing airflow mixing and accelerating axial momentum decay.

Although α and β values differ across configurations, each diffuser outlet diameter remains consistent, ensuring constant outlet area A_{out} . Under constant flow rate Q , outlet average velocity remains uniform across all configurations.

Therefore, differences among configurations primarily stem from internal flow structures (diffusion effects and swirl intensity) rather than boundary condition variations, ensuring experimental results possess sound comparability and attributability. Furthermore, this parametric design enables decoupled influence analysis, providing foundations for subsequent jet decay, diffusion, and comfort evaluations.

As illustrated in Figure 3, based on this parametric model, diffuser geometries were constructed using 3D modeling software and exported as STL files. Fused Deposition Modeling (FDM) technology was employed for 3D printing fabrication (material: PLA). To ensure experimental consistency, identical inlet conditions and installation methods were applied across all configurations, with printing precision controlled within ± 0.2 mm, and surfaces appropriately treated to minimize roughness effects.

Independent variable value ranges and configuration combinations are detailed in Tables 1.

Tab. 1. Values of the independent variables

independent variable	coded value	retrieve value		
diffusion angle	α	0	30	60
blade curvature	β	7.0	12.5	17.5

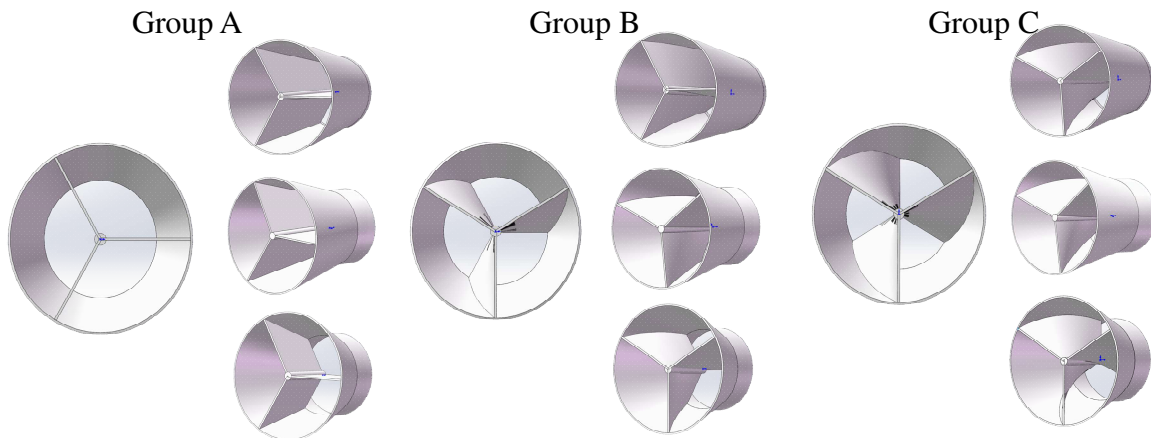


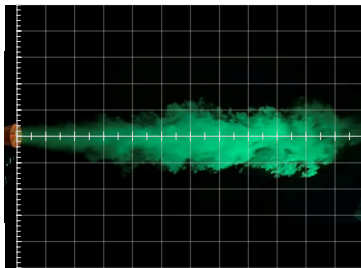
Fig. 3. Cross-sectional and Front Views of Group A B C

3. Results

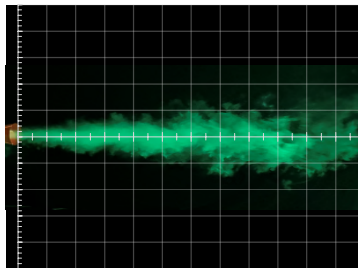
3.1 Evolution Patterns of Jet Flow Regimes

This section systematically presents quantitative and qualitative findings on how different swirl geometries influence jet characteristics. The discussion follows a logical progression from macro to micro scales, and from physical properties to comfort assessments. First, flow visualization results provide intuitive comparisons of jet morphologies produced by different diffusers. Second, in-depth quantitative analysis examines how key geometric parameters—diffusion angle (α) and blade curvature (β)—regulate core aerodynamic indicators including axial velocity decay, radial spreading, and temperature attenuation. Finally, measurement data from the “target occupied zone” evaluates the actual effectiveness of different supply modes in creating local thermal comfort environments.

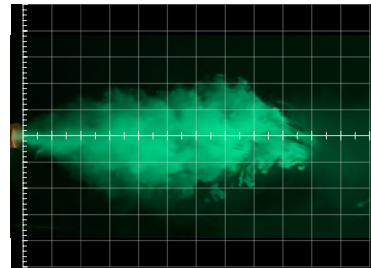
Flow field visualization experiments offer the most intuitive physical representation for understanding fundamental alterations to jet macrostructure induced by swirl diffuser geometry. Through smoke visualization across all operating conditions, we captured evolutionary patterns of jet flow regimes under different geometric parameter combinations. To systematically analyze these patterns, all configurations were categorized into three primary groups based on their core physical characteristic



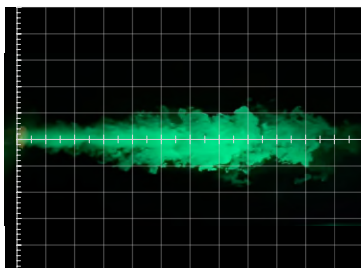
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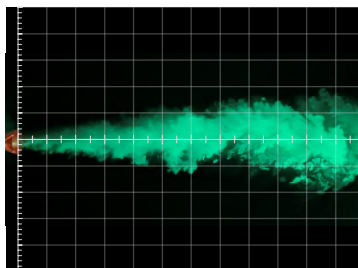
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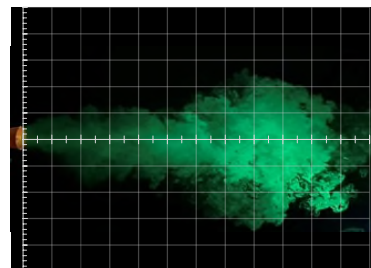
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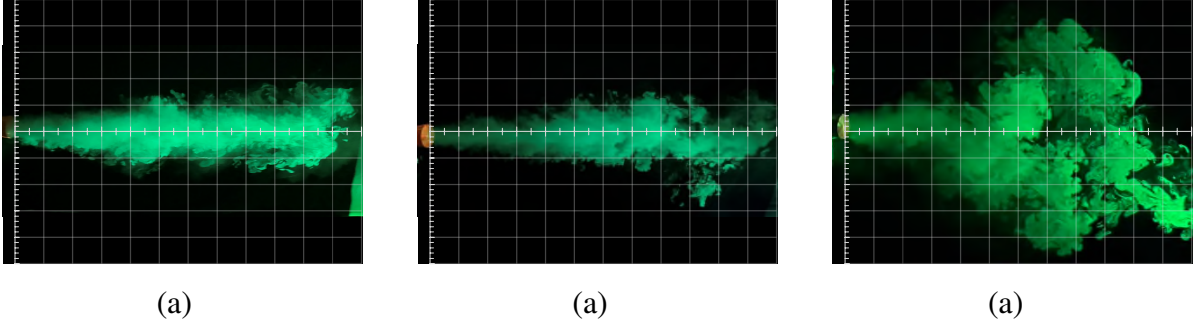


Fig. 4. Smoke flow visualization diagrams of the flow field at the central cross-section for representative air vent configurations.

Non-Swirling Conditions ($\beta=0^\circ$): “Transport-Dominated” Straight Jets

When $\beta=0^\circ$ (Group A), all configurations lack initial tangential momentum, exhibiting typical straight jet characteristics. The essence lies in highly concentrated axial momentum transport with extremely limited radial spreading. Whether the “columnar” flow from the baseline grille diffuser or the elongated “conical” jets formed by D7-0 and D12.5-0 configurations, their commonality is a stable core region with clearly defined boundaries and strong penetration. This morphology intuitively demonstrates that momentum and cooling capacity are confined within a narrow channel, with weak entrainment mixing with surroundings limited to shear layers at jet boundaries—the physical root cause of distant “cold draft” and “draft sensation.”

Swirling Conditions ($\beta>0^\circ$): “Mixing-Dominated” Flow Regime Transformation

When blade curvature is introduced (Group B $\beta=30^\circ$ and Group C $\beta=60^\circ$), flow field topology undergoes fundamental transformation. The essence of this qualitative change is the formation and development of a Central Toroidal Recirculation Zone (CTRZ), converting the jet to a highly efficient “mixing-dominated” mode. Centrifugal forces generated by swirl “fling” fluid outward, causing axial pressure to plummet and create a low-pressure zone, thereby powerfully entraining surrounding ambient air backward to form the CTRZ. This recirculation zone acts as a powerful “internal mixing engine,” not only entraining at the jet’s outer boundary but also opening new mixing interfaces internally, enabling ambient air to be efficiently drawn into the cold jet’s “heart,” achieving rapid, intense mixing. Flow morphology evolves from non-swirling “pencil-like” forms to Group B’s ($\beta=30^\circ$) distinctive “tulip-shaped” helical cones, and further to Group C’s ($\beta=60^\circ$) more “stocky” “trumpet-like” configurations. The sparse “dark core” of tracer in visualization images at the axial center intuitively confirms CTRZ existence and expansion.

Synergistic Role of Diffusion Angle α Under Swirl: Unlike its secondary role in Group A, in Groups B and C with swirl present, diffusion angle α becomes a key synergistic parameter guiding and optimizing initial expansion morphology. For instance, in the D17.5-30 configuration, centrifugal forces from swirl synergistically reinforce Coanda effect induced by large diffusion angle, causing the jet to spread along surfaces like a “film,” forming large-scale CTRZ with excellent mixing. In contrast, the D7-60 configuration’s narrow diffusion angle “constrains” strong swirl expansion, creating unique intense internal mixing. This demonstrates that precise jet morphology control can be achieved through β and α combinations.

3.2 Quantitative Analysis of Jet Aerodynamic Characteristics

3.2.1 Axial Velocity Decay

In applications of portable air conditioners in large spaces such as industrial workshops, the primary task is effective delivery of cold air to target work zones. The axial velocity decay rate directly determines jet penetration capability and effective operating distance (i.e., effective throw L_v), serving as a fundamental indicator for evaluating supply performance.

(1) Determination of Jet Axis

The jet axis is defined as the extension of the outlet's geometric centerline in the supply direction. For jets that may deflect (such as those with guide vanes), the actual airflow axis is obtained by connecting maximum velocity points across cross-sections. Velocity at measurement points along the axis is recorded as $V_{\text{axis}}(X_i)$, where X_i represents axial distance from the outlet.

(2) Dimensionless Treatment

To eliminate influences of outlet parameter differences, dimensionless characterization is adopted

$$\tilde{X}_i = \frac{X_i}{D_{\text{eq}}} \quad (6)$$

$$\tilde{V}_{\text{axis}}(X_i) = \frac{V_{\text{axis}}(X_i)}{V_0} \quad (7)$$

where V_0 is the maximum velocity at the first measurement cross-section from the outlet (serving as reference velocity), and D_{eq} is the outlet equivalent diameter.

(3) Decay Curve Fitting

In the main decay region far from the outlet, axial velocity typically follows power-law decay:

$$\tilde{V}_{\text{axis}}(\tilde{X}) = C \cdot \tilde{X}^{-n} \quad (8)$$

where C is the decay coefficient and n the decay exponent. Nonlinear least squares fitting of experimental data yields C and n values for each diffuser. Smaller decay exponent n indicates slower axial velocity decay and greater throw distance.

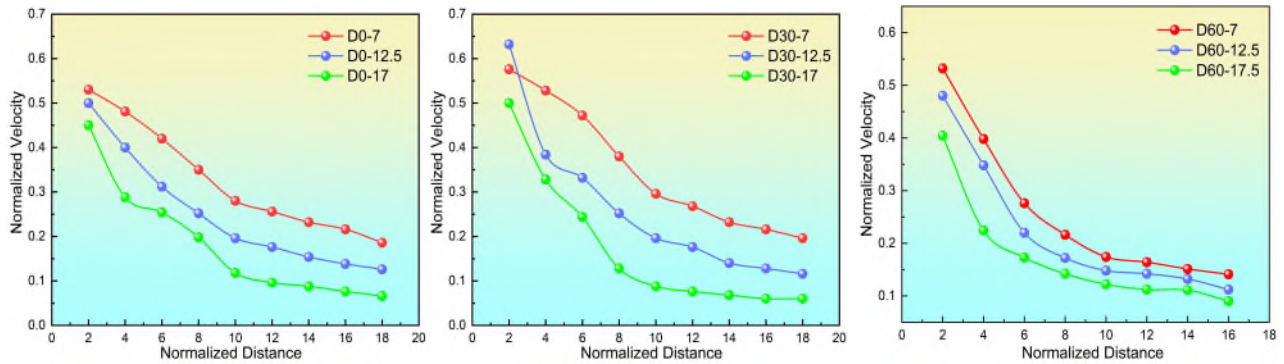


Fig. 5. Decay curves of normalized axial velocity for test outlet air supply

Tab. 2. Decay curves of dimensionless centerline velocity and power-law fitting results for various operating conditions

Group	β	α	c	n	R2
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	0°	7°	2.21	0.93	0.991
A	0°	12.5°	2.34	0.96	0.993
	0°	17.5°	2.45	1.00	0.990
	30°	7°	3.15	1.32	0.995
B	30°	12.5°	3.28	1.36	0.996
	30°	17.5°	3.40	1.41	0.994
	60°	7°	4.05	1.78	0.992
C+	60°	12.5°	4.11	1.80	0.993
	60°	17.5°	4.18	1.83	0.991

Figure 5. presents dimensionless axial velocity decay curves for all tested diffusers at 5 m/s supply velocity. All jets exhibit typical characteristics of near-field “core region” and far-field “fully developed region.” Table .2 provides dimensionless centerline velocity decay curves and power-law fitting results for different configurations.

All configurations satisfy power-law decay in the fully developed region ($x/D_{eq} > 6$), with goodness-of-fit exceeding 0.99, indicating the model accurately describes jet decay characteristics. Figure 5 illustrates dimensionless axial velocity decay curves for different diffuser configurations at 5 m/s supply velocity. All configurations exhibit typical free jet development characteristics: a potential core region in the near field and fully developed region in the far field. As dimensionless distance increases, axial velocity monotonically declines overall, displaying stable power-law decay characteristics in the far field.

Differences among configurations primarily manifest in decay rates. Under non-swirling conditions, axial velocity decays relatively slowly with gentler curved slopes; as swirl intensity increases, decay rates noticeably accelerate with steeper slopes, indicating rapid axial momentum dissipation over shorter distances. In contrast, diffusion angle variation exerts relatively weaker influence on curve morphology, primarily affecting initial expansion degree in the near field with limited impact on far-field decay trends.

Table.2 further provides power-law fitting parameters for different configurations. All configurations achieve $R^2 > 0.99$, confirming the model adequately describes axial velocity decay. Analyzing decay exponent n : non-swirling conditions ($\beta=0^\circ$) yield $n = 0.93\text{--}1.00$; when β increases to 30° , n rises to $1.32\text{--}1.41$; further increasing to 60° brings n to $1.78\text{--}1.83$, representing maximum increase of approximately 85% versus non-swirling conditions. Under fixed diffusion angle (taking $\alpha=12.5^\circ$ as example), n increases from 0.96 to 1.36 and 1.80, indicating blade curvature dominates axial velocity decay. Comparatively, diffusion angle α 's influence is limited. Under $\beta=30^\circ$, when α increases from 7° to 17.5° , n only rises from 1.32 to 1.41 (approximately 6.8% increase), suggesting it primarily adjusts initial jet expansion, playing a secondary role in decay processes. Decay coefficient C exhibits upward trend with increasing swirl intensity, rising from 2.21–2.45 to 4.05–4.18. Compared to decay exponent, C primarily affects overall decay curve level with relatively weaker control over decay rate.

Mechanistically, axial velocity decay is jointly controlled by momentum transport and turbulent mixing. As swirl intensity increases, radial diffusion and entrainment strengthen, accelerating axial momentum dissipation, manifesting as increased decay exponent and shortened

effective throw.

In summary, blade curvature β is the dominant factor controlling axial velocity decay, while diffusion angle α plays a secondary regulatory role. Considering comprehensive engineering application requirements, moderate swirl configurations (such as D12.5-30) demonstrate superior overall performance.

Referencing ASHRAE Standard 55 air velocity requirements for thermal comfort, effective throw L_v is defined as the axial distance where axis velocity first decays to threshold $V_{th} = 0.25$ m/s. By solving the equation:

$$\frac{V_{th}}{V_0} = C \cdot \left(\frac{L_v}{D_{eq}} \right)^{-n} \quad (9)$$

numerical solutions for L_v are obtained. Larger L_v indicates broader effective cooling range. Figure 3.3 presents comparative effective throw results for different diffuser configurations. Results show significant differences in effective throw with blade curvature β variation.

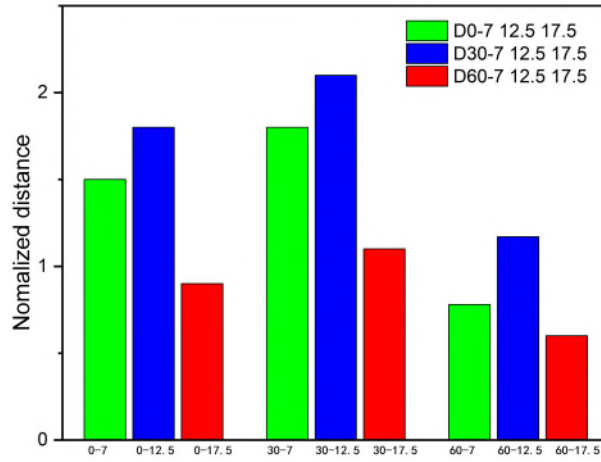


Fig. 6. Effective throw comparison of air outlets with different geometric designs

Under non-swirling conditions ($\beta=0^\circ$), all configurations achieve effective throw exceeding 4.0 m (e.g., D7-0 approximately 4.2 m), indicating strong axial transport capability. However, these configurations exhibit weak mixing, prone to causing uneven velocity distribution in target zones.

When β increases to 60° , effective throw significantly decreases below 2.0 m, indicating rapid near-field axial momentum dissipation with jets unable to achieve long-distance delivery. In contrast, moderate swirl ($\beta=30^\circ$) achieves effective throw primarily in the 2–3 m range. For example, D12.5-30's L_v is approximately 2.9 m, satisfying typical industrial work zone supply distance requirements.

L_v values exhibit pronounced nonlinear characteristics with variations in diffusion angle and curvature. As diffusion angle increases, airflow diffusion capability strengthens and entrainment effects intensify, initially elevating L_v ; however, when diffusion angle becomes excessive, airflow separation and momentum decay intensify, causing L_v to decline. Simultaneously, curvature influences L_v by affecting airflow attachment and guidance capability. Appropriately increasing curvature can enhance airflow wall-attachment effects and improve local ventilation efficiency, but excessive curvature triggers flow separation, reducing airflow stability. Therefore, optimal

matching relationships exist between diffusion angle and curvature; their synergistic optimization is critical for enhancing airflow organization performance and L_v levels. Combined with flow field analysis, these results stem from differences in momentum transport and mixing processes under varying swirl intensities: non-swirling configurations emphasize axial transport, while strong swirl configurations significantly enhance radial diffusion and entrainment, causing rapid momentum dissipation; moderate swirl conditions achieve relative balance between the two. Ultimately, through engineering evaluation of effective throw, we preliminarily identified moderate swirl configurations represented by D12.5-30, which achieve optimal balance between throw distance and mixing efficiency, demonstrating tremendous practical application potential.

3.2.2 Radial Spreading Characteristics and Coverage Range

Jet radial spreading capability determines supply coverage range and entrainment intensity with ambient air. Airflow diffusion characteristics quantitatively evaluate jets' lateral coverage capability over target areas and mix efficiency with ambient air. This study characterizes these features by analyzing evolution of velocity half-width in lateral (Y-axis) and vertical (Z-axis) directions as jets propagate axially.

(1) Definition of Half-Width Velocity

At cross-section with axial distance X_i from outlet, velocity half-width $b_{0.5v}$ is defined as: on horizontal or vertical curves passing through the jet axis, the radial distance between measurement point and axis when velocity decays to half the maximum velocity $V_{\max, \text{sec}}(X_i)$ at that cross-section. Calculation logic:

$$V(X_i, Y, Z) = 0.5 V_{\max, \text{sec}}(X_i) \quad (10)$$

This study separately calculates horizontal and vertical half-widths $b_{0.5v,y}$ and $b_{0.5v,z}$. If they differ within 5%, their average serves as representative half-width for that cross-section: $\overline{b_{0.5v}} =$

$\frac{b_{0.5v,y} + b_{0.5v,z}}{2}$ If significant asymmetry exists, analysis proceeds separately.

$$\overline{b_{0.5v}} = \frac{b_{0.5v}}{D_{\text{eq}}} \quad (11)$$

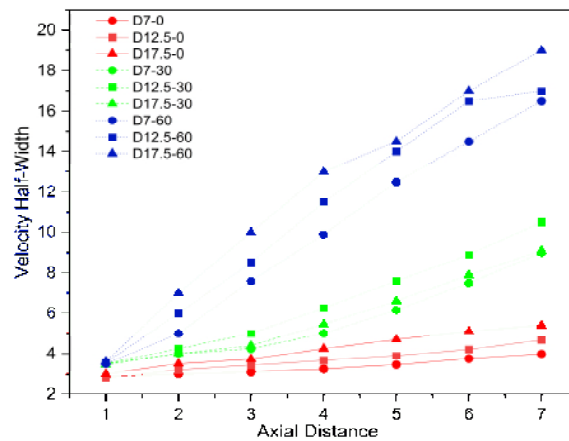


Fig. 7. Evolution of the half-width of dimensionless velocity with axial distance for air outlets of different geometric configurations.

Tab. 3. Comparison of working condition parameters

Group	β	α	k	θ
A	0°	7°	0.085	9.7
	0°	12.5°	0.090	10.3
	0°	17.5°	0.095	10.9
B	30°	7°	0.140	16.0
	30°	12.5°	0.160	18.2
	30°	17.5°	0.152	17.3
C	60°	7°	0.225	25.5
	60°	12.5°	0.235	26.6
	60°	17.5°	0.240	27.2

Experimental results indicate diffusion coefficients exhibit distinct stratification under different blade curvature conditions. For non-swirling configurations ($\beta=0^\circ$), K values maintain 0.085–0.095 range, consistent with classical free jet results. After introducing swirl, diffusion capability significantly enhances at $\beta=30^\circ$, K values increase to approximately 0.14–0.16; when β further increases to 60° , K values exceed 0.225. Results demonstrate swirl structure introduction alters jet momentum distribution, making radial expansion the dominant evolutionary mode.

Under fixed swirl intensity, diffusion angle α exhibits non-monotonic influence on diffusion behavior. At $\beta=30^\circ$, K values show initial increase then decrease with increasing α , with $\alpha=12.5^\circ$ corresponding to maximum diffusion coefficient ($K \approx 0.16$). When α is small, outlet geometric constraints limit radial development; when α is excessive, initial momentum flux declines, weakening diffusion capability.

In contrast, under strong swirl conditions ($\beta=60^\circ$), K values respond weakly to α variation, with overall fluctuation below 5%. This phenomenon indicates that under high swirl intensity, radial expansion is primarily controlled by swirl-induced mechanisms, with geometric expansion influence becoming secondary, exhibiting certain saturation characteristics.

Synthesizing results across configurations reveals D12.5-30 ($\beta=30^\circ$, $\alpha=12.5^\circ$) achieves superior balance between diffusion capability and flow stability. Its diffusion coefficient and coverage range both satisfy engineering application requirements, demonstrating excellent comprehensive performance.

Within the fully developed region of the jet, the dimensionless half-width maintains a robust linear correlation with the dimensionless axial distance. This expansion behavior is characterized by the following linear model:

$$\widetilde{b_{0.5v}} = K\tilde{X} + B \quad (12)$$

The diffusion angle provides a clear benchmark: a larger θ indicates a broader lateral reach per unit of travel, translating to a more potent capacity for entrainment and mixing with the surrounding ambient air.

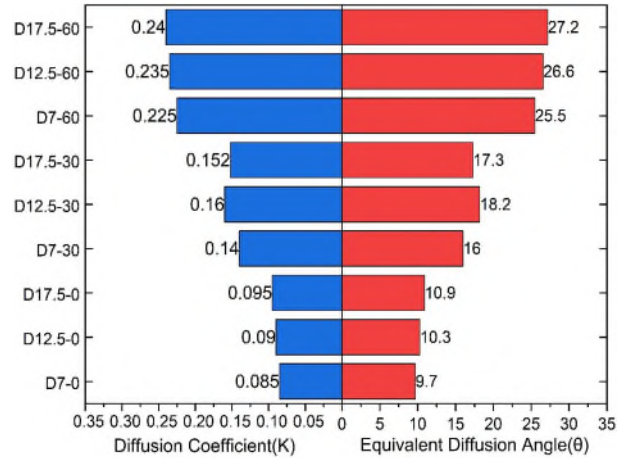


Figure.8. Comparative Analysis of Diffusion Coefficients and Equivalent Diffusion Angles across Diffuser Geometries.

Figure.8.provides a quantitative visualization of how these parameters dictate jet coverage. Compared to the baseline grille diffuser, every swirl-enabled configuration demonstrates a profound leap in diffusion capability. Even the D7-30 configuration—the weakest swirl condition—yields a K value of 0.14, a 75% improvement over the baseline. At the high end of the spectrum, the D17.5-60 configuration reaches a K of 0.24 and a θ of approximately 27, effectively tripling the radial coverage of the baseline. This confirms that swirl is the fundamental mechanism for fundamentally restructuring the jet and optimizing coverage efficiency. At a moderate swirl intensity ($\beta=30^\circ$), the diffusion coefficient K does not increase monotonically with the diffusion angle α . This reveals a critical Synergistic Effect: the centrifugal force generated by the swirl serves as the “internal engine” for radial expansion, while the diffuser’s physical angle α provides the “guiding conduit.” When α is too narrow (7°), the conduit constricts the initial jet and stifles the centrifugal potential. Conversely, an excessive angle (17.5°) can force the airflow into an abrupt, steep turn, triggering localized flow separation or energy dissipation that hampers overall diffusion. The D12.5-30 combination, therefore, achieves an optimal calibration of “power” and “guidance.” “The marginal gains realized by increasing α are notably limited (rising only from 0.225 to 0.240). This suggests that once swirl intensity crosses a certain threshold, the resulting centrifugal force becomes the absolute dominant factor in the expansion process. At this stage, the guiding influence of the physical boundary (α) is vastly diminished—a state termed the Saturation Phenomenon. In this regime, further widening the diffusion angle yields diminishing marginal returns in terms of coverage area.

Because of its superior synergistic properties, the D12.5-30 configuration achieves the most effective balance between spreading capability and flow stability, representing the optimal performance profile among the tested conditions.

3.3 Evaluation and Analysis of Local Thermal Comfort

To comprehensively evaluate how different diffuser configurations influence airflow distribution quality in practical applications, this study establishes two critical evaluation metrics within a predefined target zone: the Coefficient of Variation of Velocity (COV) and the Comfortable Air Velocity Coverage Ratio (η_{comfort}).

3.3.1 Definition of Target Zone

The spatial configuration of the target zone is based on typical spot cooling application scenarios. This study defines the target zone as: Axial range: $1.0 \text{ m} \leq X \leq 2.0 \text{ m}$ from the outlet (covering the fully developed jet region) Vertical range: $0.6 \text{ m} \leq Z \leq 1.1 \text{ m}$ above floor level (corresponding to the torso activity zone for seated occupants) Lateral range: $-0.5 \text{ m} \leq Y \leq 0.5 \text{ m}$ (covering single-person workstation width)

To capture velocity distribution characteristics within this region, multiple representative measurement cross-sections were established with uniformly distributed grid points (grid spacing: $\Delta Y = \Delta Z = 0.1 \text{ m}$), totaling 49 valid measurement points.

3.3.2 Coefficient of Variation of Velocity (COV_v)

(1) Definition and Calculation

The velocity uniformity coefficient quantifies the dispersion degree of the airflow velocity field within the target zone, defined as the ratio of the standard deviation of velocity (σ_v) to the mean velocity ($\bar{V}$) across all measurement points in the region:

$$\text{COV}_v = \frac{\sigma_v}{\bar{V}} \times 100\% \quad (13)$$

$$\sigma_v = \sqrt{\frac{1}{N} \sum_{i=1}^N (V_i - \bar{V})^2} \quad (14)$$

V_i represents the local time-averaged air velocity at the i th measurement point, and N denotes the total number of measurement points within the target zone.

Lower COV_v indicates more uniform velocity distribution within the target zone, with no localized high-velocity zones (causing draft discomfort) or low-velocity dead zones (compromising cooling effectiveness). Conversely, higher COV_v signifies strong velocity field dispersion and non-uniform airflow distribution, adversely affecting occupant thermal comfort. This metric directly reflects the comprehensive performance of diffuser design in the far-field region and serves as a critical feedback parameter for optimizing outlet configurations.

Tab. 4. Velocity Uniformity Coefficient COV_v in Target Zone under Different Diffuser Configurations

Group	β	α	Vavg (m/s)	σ (m/s)	COV _v (%)
A	0°	7°	0.283	0.116	40.937
	0°	12.5°	0.290	0.109	37.611
	0°	17.5°	0.313	0.143	45.645
B	30°	7°	0.297	0.107	35.930
	30°	12.5°	0.239	0.098	40.999
	30°	17.5°	0.284	0.122	43.171
C+	60°	7°	0.253	0.095	37.659
	60°	12.5°	0.276	0.091	32.731
	60°	17.5°	0.269	0.099	37.879

As shown in Table 4, COV_v values across configurations range from 32.7% to 45.6%,

indicating persistent velocity non-uniformity within the target zone at 100 m³/h operation. As blade curvature β increases, COV_v exhibits an overall declining trend. For instance, at $\alpha = 17.5^\circ$, COV_v decreases from 45.6% ($\beta = 0^\circ$) to 37.9% ($\beta = 60^\circ$). This result demonstrates that swirl enhances radial diffusion and entrainment processes, thereby reducing velocity gradients and improving regional uniformity.

Under non-swirling conditions ($\beta = 0^\circ$), COV_v exhibits non-monotonic variation with diffusion angle α , with optimal uniformity achieved at $\alpha = 12.5^\circ$. This suggests that moderate geometric expansion benefits velocity distribution improvement, while excessive diffusion angles may induce flow instability, paradoxically reducing uniformity.

Among different parameter combinations, the D12.5-60 configuration achieves the lowest COV_v (32.7%), while D17.5-0 performs worst (45.6%). Results indicate that moderate diffusion angle combined with strong swirl achieves superior balance between expansion and mixing. D17.5-0 exhibits pronounced coexistence of central high-velocity zones and peripheral low-velocity regions with substantial velocity gradients; in contrast, D12.5-60 demonstrates reduced high-velocity zone intensity with more uniform distribution, significantly fewer low-velocity regions, and an overall smoother velocity field

3.3.3 Comfortable Air Velocity Coverage Ratio

Building upon the evaluation of target zone airflow uniformity, to further characterize the impact of different velocity ranges on occupant thermal comfort, this study introduces the proportions of comfort zones, low-velocity zones, and high-velocity zones as supplementary evaluation metrics.

According to ASHRAE Standard 55 (2020) and GB/T 18883-2002, this study classifies measurement point velocities within the target zone into three intervals: Low-velocity zone: $V_i < 0.1$ m/s Comfort zone: $0.1 \text{ m/s} \leq V_i \leq 0.6$ m/s High-velocity zone: $V_i > 0.6$ m/s

Based on this classification, the proportions of these three zones are defined as:

$$\eta_{\text{comfort}} = \frac{N_{\text{comfort}}}{N_{\text{total}}} \times 100\% \quad (15)$$

$$\eta_{\text{low}} = \frac{N_{\text{low}}}{N_{\text{total}}} \times 100\% \quad (16)$$

$$\eta_{\text{high}} = \frac{N_{\text{high}}}{N_{\text{total}}} \times 100\% \quad (17)$$

Since each measurement point is uniquely assigned to one of these three categories, the following conservation relationship holds:

$$\eta_{\text{comfort}} + \eta_{\text{low}} + \eta_{\text{high}} = 100\% \quad (18)$$

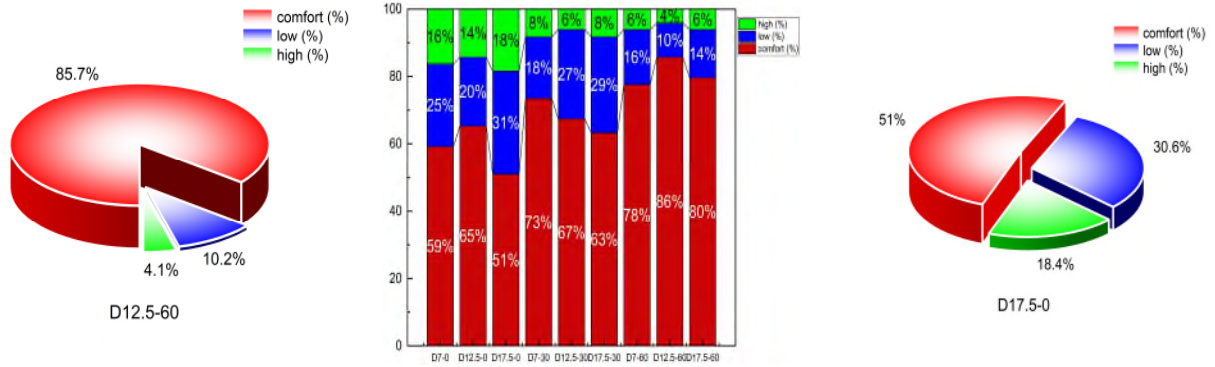


Figure.9. Comparison of Typical Working Condition Zones and Comfortable Wind Speed Compliance Rate(D12.5-60 Optimal & D17.5-0 Worst)

Tab. 5. Comfortable Air Velocity Coverage Ratio and Zone Proportions in Target Zone under Different Diffuser Configurations

Group	β	α	N_{total}	N_{comfort}	N_{low}	N_{high}	η_{comfort}	η_{low}	η_{high}
A	0°	7°	49	29	12	8	59.2	24.5	16.3
	0°	12.5°	49	32	10	7	65.3	20.4	14.3
	0°	17.5°	49	25	15	9	51.0	30.6	18.4
B	30°	7°	49	36	9	4	73.5	18.4	8.2
	30°	12.5°	49	33	13	3	67.3	26.5	6.1
	30°	17.5°	49	31	14	4	63.3	28.6	8.2
C+	60°	7°	49	38	8	3	77.6	16.3	6.1
	60°	12.5°	49	42	5	2	85.7	10.2	4.1
	60°	17.5°	49	39	7	3	79.6	14.3	6.1

As shown in Tab. 5. and Figure.9, the comfortable air velocity coverage ratio η_{comfort} across configurations ranges from 51.0% to 85.7%, indicating significant differences in comfortable airflow coverage capability among diffuser designs.

As blade curvature β increases, η_{comfort} exhibits an overall upward trend. At $\alpha = 12.5^\circ$, this value improves from 65.3% to 85.7%; at $\alpha = 17.5^\circ$, it rises from 51.0% to 79.6%. This result demonstrates that swirling effectively promotes jet mixing, bringing more zones within comfortable velocity ranges.

In contrast, the influence of diffusion angle α exhibits non-monotonic characteristics. Under identical blade curvature conditions, $\alpha = 12.5^\circ$ consistently yields higher η_{comfort} , suggesting that moderate diffusion facilitates reasonable velocity decay and spatial distribution, while excessive diffusion angles may trigger flow separation and diminish comfort.

Optimal Configuration: The D12.5-60 configuration achieves the highest η_{comfort} (85.7%), while its η_{low} and η_{high} stand at 10.2% and 4.1%, respectively—the lowest among all configurations. Results indicate this configuration excels in suppressing both low-velocity and excessively high-velocity zones.

Combined with the earlier COV_v analysis, this configuration achieves optimal balance between uniformity and comfort, demonstrating that the coupling effect of moderate swirl with intermediate diffusion angle fosters a stable and rationally distributed velocity field.

Worst Configuration: The D17.5-0 configuration exhibits the lowest η_{comfort} (51.0%), with η_{low} and η_{high} reaching 30.6% and 18.4%, respectively, displaying pronounced non-uniform velocity distribution characteristics. Combined with its elevated COV_v results, this configuration clearly manifests significant high-velocity core zones and extensive low-velocity regions, resulting in reduced comfort zone coverage and poor overall thermal comfort performance.

4 Discussion

4.1 Swirl-Induced Flow Regime Transition Mechanisms

Based on the experimental results presented in Chapter 3, the influence of swirl diffuser geometric parameters on jet structure and thermal comfort performance has been quantitatively characterized. However, mere phenomenological descriptions remain insufficient to unveil the underlying physical essence. This chapter builds upon experimental data to systematically analyze the swirl-induced flow regime transition processes and their macroscopic performance responses from a fluid dynamics perspective, with particular emphasis on elucidating the intrinsic mechanisms by which geometric parameters regulate flow field topology evolution and their engineering significance.

Experimental results demonstrate that blade curvature β serves as the primary controlling parameter determining jet flow morphology. By altering initial swirl intensity, it triggers a transition from momentum-dominated to mixing-dominated regimes. The core characteristic of this transition lies in the formation and development of the Central Toroidal Recirculation Zone (CTRZ). The CTRZ not only reconstructs near-field flow structures but also significantly alters momentum transport pathways, thereby exerting decisive influence on diffusion capability, velocity decay characteristics, and spatial uniformity. Therefore, establishing the correlation between “swirl intensity—CTRZ structure—macroscopic performance” is key to understanding swirl jet behavior. To further reveal the dynamic essence of this process, it is necessary to analyze flow regime evolution under different swirl intensities from the perspective of vortex breakdown mechanisms.

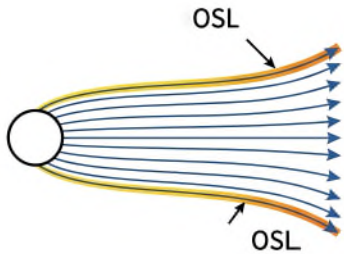
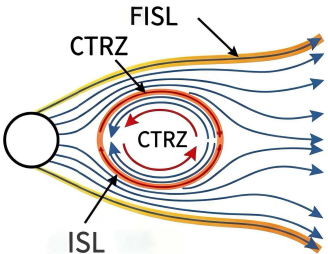
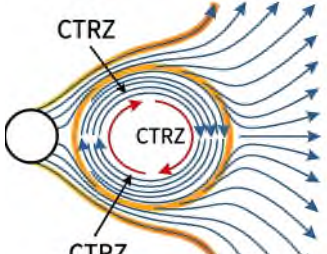
$$v_{\theta,0} \approx U_{\text{axial},0} \tan(\beta) \quad (19)$$

where $v_{\theta,0}$ represents the tangential velocity component at the outlet, $U_{\text{axial},0}$ the axial velocity component, and $\tan(\beta)$ the blade deflection angle. This establishes a flow structure with rotational characteristics within the jet. This tangential momentum induces a radial pressure gradient whose distribution satisfies:

$$\frac{\partial p}{\partial r} = \rho \frac{v_{\theta}^2}{r} \quad (20)$$

When swirl intensity reaches a certain threshold, an adverse axial pressure gradient emerges, subsequently triggering the characteristic vortex breakdown phenomenon. This causes axial flow deceleration, stagnation, or even reversal, ultimately forming a stable CTRZ structure.

Tab. 6. Comparison of working condition parameters

Group	β	α	k
Flow Field Topology (Schematic)			
Core Physical Process	Momentum transport dominance	Flow regime transition	Momentum mixing dominance
Key Parameters	$K = 0.090$ $n = 0.96$ $L_r = 0$	17.5° $K = 0.160 (+78\%)$ $n = 1.36 (+42\%)$ $L_r \approx 3De$	0.095 $K = 0.235 (+161\%)$ $n = 1.80 (+88\%)$ $L_r \approx 4.5De$

4.2 Synergistic Relationships among Multiple Evaluation Indicators and Comprehensive Performance Assessment

To avoid one-sidedness inherent in single-indicator evaluation, this study constructs a multi-evaluation system encompassing flow characteristic indicators and target zone performance indicators for systematic analysis of different diffuser configurations. These indicators are not mutually independent but form a hierarchical mapping relationship from “flow structure $\rightarrow$ velocity distribution $\rightarrow$ comfort performance” through jet development processes

To achieve unified performance evaluation of different diffuser configurations, this study constructs the Comprehensive Performance Index (CPI). This metric comprehensively characterizes airflow performance from three aspects: thermal comfort, velocity uniformity, and jet action range, expressed as:

$$CPI = w_1 \eta_{comfort} + w_2 (1 - COV_v) + w_3 (L_v / L_{ref}) \quad (21)$$

where $\eta_{comfort}$ represents comfortable air velocity coverage ratio within the target zone, COV_v denotes velocity uniformity coefficient, L_v indicates effective throw, and L_{ref} is reference throw. Weight coefficients w_i satisfy $\sum w_i = 1$.

For local ventilation thermal comfort optimization objectives, weight allocation is as follows:

$$w_1 = 0.40, w_2 = 0.25, w_3 = 0.15$$

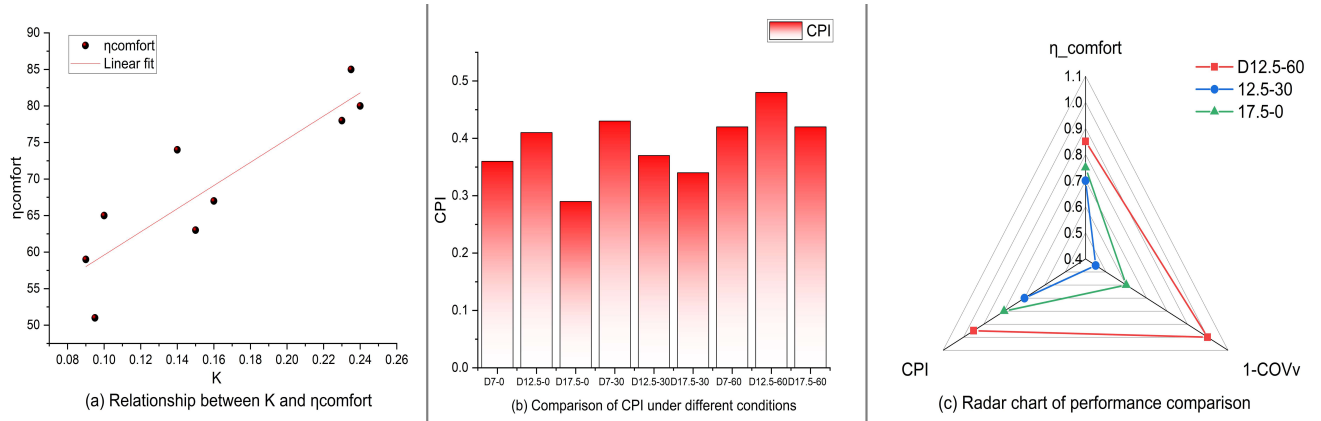


Figure.10. Integrated analysis of diffusion characteristics, thermal comfort, and comprehensive performance under different operating conditions

From the perspective of inter-indicator correlational characteristics, radial diffusion coefficient K plays a critical bridging role in the multi-indicator system. On one hand, increasing K signifies enhanced lateral jet expansion capability, thereby weakening central high-velocity zones and elevating peripheral low-velocity zone velocities; on the other hand, this process directly transforms velocity distribution morphology within target zones. As shown in Figure 10(a), K exhibits significant positive correlation with comfortable velocity coverage ratio η_{comfort} , indicating that enhanced radial diffusion helps increase the area proportion within comfortable velocity ranges in target zones. Furthermore, significant negative correlation exists between velocity uniformity indicator COV_v and η_{comfort} (see trend comparison in Figure 10 (a)), indicating spatial dispersion degree of velocity fields serves as a key mediating variable affecting comfort. Lower COV_v corresponds to more uniform velocity distribution, thereby reducing zones with excessively high or low local velocities and elevating overall comfort levels.

At the comprehensive evaluation level, this study introduces the Comprehensive Performance Index (CPI) for unified quantification of each configuration. Based on the above correlational relationships, CPI comparative results for different configurations are shown in Figure 10(b). Results indicate significant comprehensive performance differences among configurations, with D12.5-60 achieving the highest CPI value, demonstrating optimal balance among comfort, uniformity, and effective coverage range; in contrast, D17.5-0 exhibits the lowest CPI, with performance disadvantages primarily stemming from higher velocity dispersion and lower comfortable coverage ratio.

To further reveal synergistic and trade-off relationships among multiple indicators, Figure 10(c) presents multi-dimensional performance radar charts for typical configurations. It can be observed that the D12.5-60 configuration demonstrates high and balanced performance across all evaluation dimensions, while D17.5-0 exhibits pronounced imbalance characteristics—coexistence of high η_{high} and high η_{low} —reflecting typical “central direct blow + peripheral stagnation” flow structure.

In summary, radial diffusion capability serves as the core control parameter connecting flow characteristics with thermal comfort, while multi-indicator synergistic analysis methods

effectively reveal coupling mechanisms among different design parameters, providing reliable foundations for diffuser structure optimization.

4.3 Comprehensive Evaluation Results of Nine Experimental Configurations via CPI

Comprehensive evaluation of nine experimental configurations is summarized in the following table:

Tab. 7. Comprehensive Evaluation Results of Nine Experimental Working Conditions

Group	β	α	n	K	$L_{v,0.5}$	COV_v	η_{comfort}	CPI	Grade
A	0°	7°	0.89	0.082	4.3	43.8	60.2	0.371	C
	0°	12.5°	0.96	0.090	4.2	42.1	65.3	0.392	C
	0°	17.5°	1.05	0.098	3.6	45.6	51.0	0.331	D
B	30°	7°	1.28	0.145	3.2	39.4	68.1	0.395	C+
	30°	12.5°	1.36	0.160	2.9	37.2	70.5	0.402	B-
	30°	17.5°	1.42	0.153	3.0	38.1	69.8	0.400	B-
C+	60°	7°	1.71	0.228	2.3	34.5	78.3	0.449	B
	60°	12.5°	1.80	0.235	2.1	32.7	85.7	0.478	A-
	60°	17.5°	1.85	0.239	2.2	33.8	81.2	0.462	B+

Principal Findings from Comprehensive Evaluation:

D12.5-60 (CPI = 0.478, Grade A-): Optimal comprehensive performance, demonstrating excellence in the two most critical dimensions—thermal comfort ($\eta_{\text{comfort}} = 85.7\%$) and velocity uniformity ($COV_v = 32.7\%$). Although effective throw is shortest (2.1 m), it still satisfies the minimum throw requirement established by this study (≥ 2.0 m), achieving the “comfort optimization” objective.

D17.5-60 (CPI = 0.462, Grade B+): Second-best comprehensive performance, with η_{comfort} (81.2%) and $L_{v,0.5}$ (2.2 m) both slightly superior to D17.5-30, representing a superior choice under strong swirl conditions that balanced distance.

D17.5-0 (CPI = 0.331, Grade D): Worst comprehensive performance, primarily due to aforementioned Coanda effect instability causing extremely low η_{comfort} (51.0%) and extremely high COV_v (45.6%), ranking “last” among all configurations.

Three $\beta = 0^\circ$ configurations (Grades C~C): Overall at “passing” level, with D12.5-0 (CPI = 0.392) performing best, primarily because its moderate diffusion angle avoids wall-attached flow separation, delivering relatively stable comprehensive performance.

Three $\beta = 30^\circ$ configurations (Grades B- ~ C+): Show improvement compared to $\beta = 0^\circ$ configurations but with limited enhancement, residing at “transition zone” level. Among them, D12.5-30 (CPI = 0.402) performs optimally, confirming the “optimal matching” of $\alpha = 12.5^\circ$ with $\beta = 30^\circ$.

This comprehensive evaluation clearly establishes the overall performance superiority of “swirl diffusers” (especially $\beta = 60^\circ$ configurations) relative to “straight flow diffusers” ($\beta = 0^\circ$), providing quantifiable comprehensive performance evidence for engineering promotion and application.

5 Conclusions

This study systematically addresses the issue of poor local cooling performance and low thermal comfort in portable air conditioners (PACs) arising from suboptimal diffuser design. Through a comprehensive experimental investigation of nine swirl diffusers with varying geometric parameters—namely blade curvature (β) and diffusion angle (α)—the underlying airflow organization mechanisms are elucidated, and quantifiable engineering guidance for high-performance PAC design is established. The main conclusions are as follows:

1. Blade curvature (β) is identified as the decisive factor governing the macroscopic characteristics of the jet. The introduction of swirl ($\beta > 0^\circ$) fundamentally alters the jet mixing regime, shifting it from an inefficient “transport-dominated” mode to an efficient “mixing-dominated” mode. Physically, this transition is driven by the formation of a central toroidal recirculation zone (CTRZ), which substantially enhances entrainment and momentum exchange between the jet and the ambient air. Consequently, the radial diffusion capacity (K) increases by up to 161%, while the axial velocity decay rate (n) accelerates by up to 88%.

2. Among all tested configurations, D12.5–60 ($\beta = 60^\circ$, $\alpha = 12.5^\circ$) is identified as the optimal design. This configuration achieves a high comfort compliance rate η_{comfort} of 85.7% within the target zone, while minimizing discomfort regions associated with draught sensation and airflow stagnation. It represents an optimal balance among strong mixing efficiency, uniform spatial coverage, and a sufficient effective throw ($L_{v,0.5} \approx 2.1$ m).

3. For the first time, a clear “trilemma” relationship is quantitatively established among effective throw ($L_{v,0.5}$), radial diffusion (K), and velocity uniformity (COV_v). The results demonstrate that improvement in any single performance metric is inevitably achieved at the expense of others. This finding provides a theoretical basis for performance trade-offs in the early stages of engineering design, challenging the conventional expectation of simultaneously maximizing all metrics.

4. A set of practical engineering design guidelines is proposed based on the experimental findings. These include a parametric design strategy prioritizing blade curvature (β) with coordinated optimization of diffusion angle (α); the adoption of $\eta_{\text{comfort}} \geq 80\%$ as a benchmark for high-performance design; and the explicit identification of the combination of large diffusion angles with zero swirl as a high-risk configuration to be avoided.

In summary, local airflow organization based on swirl diffusion represents a supply strategy characterized by high mixing efficiency, wide coverage, and enhanced thermal comfort. It can significantly improve local thermal comfort and cooling efficiency for workers in high-temperature environments such as industrial workshops. Despite these important findings, several limitations should be acknowledged. First, all participants in this study were healthy young females; male subjects, elderly individuals, people with varying physiological conditions, and actual workers were not included, which limits the representativeness and generalizability of the results. Second, the experiments were conducted in a controlled climate chamber, without fully accounting for complex real-world factors such as dust, body posture, and high humidity, all of which may influence cooling performance, human heat dissipation, and thermal comfort evaluation. Third, the

experimental conditions were idealized. The diffuser was installed horizontally, and practical boundary conditions—such as wall effects, installation angles, and background airflow—were not considered. In addition, the outlet turbulence intensity of the experimental setup (5–8%) was lower than that of commercial products (10–15%), which may affect the applicability of the results to real systems. Fourth, due to experimental constraints and safety considerations, each test was limited to 20 minutes. However, in real high-temperature working environments, prolonged exposure (1–2 hours or more) is common, and extended cooling may induce physiological adaptation, including cardiovascular load redistribution, changes in sweating regulation, and dynamic shifts in thermal comfort. These effects were not addressed in the present study.

Accordingly, future research should expand the sample size to include participants of different genders, ages, and physical conditions, as well as actual workers, to improve representativeness. Longer-duration experiments and field studies in real working environments are also needed to validate the sustained performance of head–neck cooling strategies under complex conditions, thereby enhancing the generalizability and engineering applicability of the findings.

Finally, although the present results contribute to optimizing diffuser design in air-conditioning systems, they do not directly confirm reductions in energy consumption. Swirl diffusers have the potential to lower system energy use and reduce carbon emissions without compromising thermal and airflow comfort. This hypothesis warrants further investigation to strengthen the practical significance and broader applicability of the study.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRedit authorship contribution statement

Jue Wang: Conceptualization, Investigation, Methodology, Formal analysis, Project administration, Writing—Original draft, Writing—Review & Editing, Funding acquisition. **Siyu Yang:** Conceptualization, Investigation, Methodology, Data curation, Writing—Original draft, Writing—Review & Editing, Formal analysis. **Gang Bai:** Formal analysis, Writing—Review & Editing. **Yang Guang:** Formal analysis, Writing—Review & Editing.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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