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A Study on the Enhancement of $PM_{2.5}$ Air Purification Capability in Cyclone Separators with Curved Structures Based on CFD Simulation

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Abstract: Driven by the demand for purifying indoor air from particulate matter, this study has carried out systematic numerical research on the effect of cyclone separator geometry on the performance of $PM_{2.5}$ filtration. A comprehensive CFD analysis system is constructed based on three cone segments generatrices: straight, concave, and convex. The continuous phase in the simulation adopts the Reynolds Stress Model (RSM) due to its high ability to predict the strong anisotropic turbulent flow inside the cyclone separator. The particle phase in the present study is simulated through the Discrete Phase Model (DPM) by the Lagrangian method and considers the effects of drag force, centrifugal force, and turbulence diffusion to predict the migration and deposition process of particles with various diameters. From the results, the convex generatrix shows great superiority in capturing fine particles, obtaining a high efficiency of $PM_{2.5}$ separation up to 82.4% and a small cut-off diameter down to 2.1 μm. In comparison, the concave generatrix outperforms in reducing the pressure drop and optimizing the energy efficiency ratio, while the straight generatrix ranks in between. The results show that the reasonable control of geometric curvature can significantly improve the flow field stability and particle distribution characteristics.

Keywords: Cyclone separator; $PM_{2.5}$; CFD; Grade efficiency

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1. Introduction

As industrialization and urbanization advance rapidly, air quality safety has become a key issue for society. Taking Shanghai as an example, indoor concentration of $PM_{2.5}$ changes periodically due to such reasons as population, traffic, and cooking [1]. However, traditional ways of purifying air, including mechanical filters, electrostatic precipitation and photocatalysis, are inefficient in many aspects: filters require frequent change of consumable components, consume significant amounts of energy and produce considerable noise; electrostatic precipitation creates undesirable products, requires complicated maintenance procedures, and photocatalysis depends on light sources and can hardly provide stable results for a long time period [2–5]. Aiming at indoor scenes such as home and office, this paper constructs an air purification system that integrates the structural design of curve cyclone separator and CFD numerical simulation, regulates the geometric parameters and internal flow field of cyclone separator, accurately predicts the separation efficiency and pressure drop characteristics of PM2.5, and explores the best combination of structural parameters, so as to provide support for improving the environment, reducing risks and promoting urban green development.

Traditional PM2.5 air purification methods primarily rely on physical or chemical technologies such as mechanical filters, electrostatic precipitation, and photocatalysis. Although these approaches can reduce indoor PM2.5 concentrations in the short term, they are limited by efficiency decay, high energy consumption, secondary pollution, and high maintenance costs [6]. For instance, HEPA filters are prone to clogging, electrostatic purifiers may generate by-products and suffer from efficiency decline, and photocatalytic methods exhibit insufficient stability [7]. By contrast, cyclone separators are simple in structure, durable and reusable, and thus have application potential. However, their low capture efficiency for fine particles ≤ 2.5 μm limits their widespread adoption [8].

As a result of the advancements in CFD technology, structural optimization of cyclone separators has gained great attention recently. Parameters such as the design of the inlet, cylinder geometry, and cone angle affect the flow field inside the separator and the trajectory of the particles [9]. The Reynolds Stress Model (RSM) and Large Eddy Simulation (LES) have been employed to simulate the turbulence phenomenon. RSM models vortices, whereas LES increases the accuracy of the simulation for the separation of sub-micron particles. As far as structural optimization is concerned, a curved conical section is one of the most important methods for enhancing efficiency [10]. This is because a curved conical section can affect the vortex intensity and particle residence time. The research shows that the design of a symmetrical double inlet and variable diameter cone section can reduce the pressure drop and improve the PM2.5 separation efficiency.

Overall, research on cyclone separators for indoor PM2.5 purification has shifted from empirical design to precise CFD-based optimization, exhibiting trends toward miniaturization, low energy consumption, and intelligent operation. In the future, by integrating multi-scale simulation, experimental validation, and intelligent optimization algorithms, novel cyclone-based air purification solutions are expected to be realized.

This project will establish a method for cyclone separator air purification based on CFD numerical simulation and geometric structure optimizations. The proposed approach is capable of rapidly and accurately predicting the separation performance of cyclone separators under different structural parameters and operating conditions (PM2.5 capture efficiency, cut-off particle size, pressure drop, etc.). Firstly, a parameterizable simulation model of the cyclone separator will be constructed, enabling visual analysis of internal flow field characteristics and particle motion patterns. Subsequently, the separation performance of different conical sections, including straight, concave, and convex profiles, will be compared to identify key geometric variables. Finally, low-energy air purification design solutions suitable for domestic and office environments will be proposed, providing theoretical and technical guidance for indoor PM2.5 control.

2. Design of cyclone separator

2.1. Principle of the cyclone separator

The cone section of the traditional cyclone separator is designed in a straight line, and the fluid flow is prone to turbulence disturbance, boundary layer separation, and other problems, resulting in limited separation efficiency, such as insufficient classification accuracy of fine particles and high energy consumption. In this design, the spline curve is introduced to reconstruct the internal cone section profile of the cyclone separator to improve the fluid flow characteristics.

The mechanical aspects of the radial forces that act on particles within the hydrodynamic behavior of the hydro cyclone with the curved profile are as follows: Centrifugal force (FC), radial pressure gradient force (FB), Stokes drag force (FD), and Magnus lift (FM). Of all these mechanical forces, the centrifugal force and the radial pressure gradient force form the most significant forces in the radial motion of the particles, which together determine the radial motion trajectory of particles. See **Table 1**.

Table 1. Radial forces acting on particles in a hydro cyclone

Force name	Formula	Number
Fc	$F_c = m\frac{v_t^2}{r} = \frac{\pi\rho_p d_p^2 \frac{v_t^2}{r}}{6}$	(2)
F_B	$F_p = v_p\rho_f\frac{v_t^2}{r} = \frac{\pi D_p^3 v_t^2}{6r}\rho_f$	(3)
F_D	$F_d = 3\pi D_p u v_r$	(4)
F_M	$F_m = k\rho_f D_p^3 \omega v_r$	(5)

2.2. Design of structural parameters for cyclone separators

In the geometric design of the cyclone separator, the cylindrical-cone generatrix is usually based on a linear structure, that is, a constant cone rate is formed by a linear connection between the inlet cylindrical radius and the outlet radius. This straight generatrix stands as the simplest geometric construction and contributes to preserving gas flow continuity through the cylinder–cone transition. However, a straight conical section alone often fails to balance separation efficiency and pressure drop when finer regulation of the flow field characteristics is sought. Spline curves are therefore introduced to adjust the curvature of the straight generatrix. Bending the middle section of the curve inward produces a concave generatrix, which shortens the radial migration path of particles and, in turn, lowers the pressure drop. When the curve extends outward in the middle section, forming an outwardly convex bus bar, it helps to enhance the centrifugal force and the particle retention time, thereby improving the capture efficiency of fine particles. Because the three profiles keep the same parameters at both ends, the transition from the straight profile to the concave or convex generatrix can be realized continuously by changing the sign of the curvature parameter, thus yielding a set of geometric schemes that can be systematically compared. See **Table 2**.

The equation for a K-order spline curve is expressed as follows:

$$P(t) = \sum_{i=1}^{n+1} B_{i,k}(t)P_i, t \in [0,1] \tag{7}$$

Table 2. Dimensional parameters of the cyclone separator

Component	Symbol	Size (mm)
Overflow pipe diameter	Φ_1	35
Overflow pipe height	h3	138.6
Column section height	h4	150
Conical section height	h5	225
Column section diameter	Φ_2	75
Outlet diameter	Φ_3	38
Inlet pipe length	h1	45
Inlet pipe width	h2	30

Figure 1 compares three typical generatrix profiles for the conical section of a cyclone separator, namely straight, concave and convex. The straight generatrix is formed by a linear connection between the inlet radius Φ2 = 78 mm and the outlet radius Φ3 = 38 mm, with a conical section height of h5 = 225 mm. This is the most common baseline structure. The concave generatrix contracts inwards in the middle section. Compared with the straight profile, it exhibits a faster radial convergence, which can shorten the particle migration path. In the middle portion, the concave generatrix tends to contract inwardly. When compared to the straight generatrix, it shows faster radial contraction that may help reduce the distance of travel of particles. However, in the case of the convex generatrix, it is extended outwardly in the middle portion, and hence there is fast convergence of the fluid in the first portion and leveling in the last portion, thereby helping to enhance the centrifugal separation of particles. Since the geometric parameters at the two ends remain constant, the three generatrices differ solely in the curvature of their middle sections. This sets up a uniform geometric foundation for carrying out comparative CFD simulations.

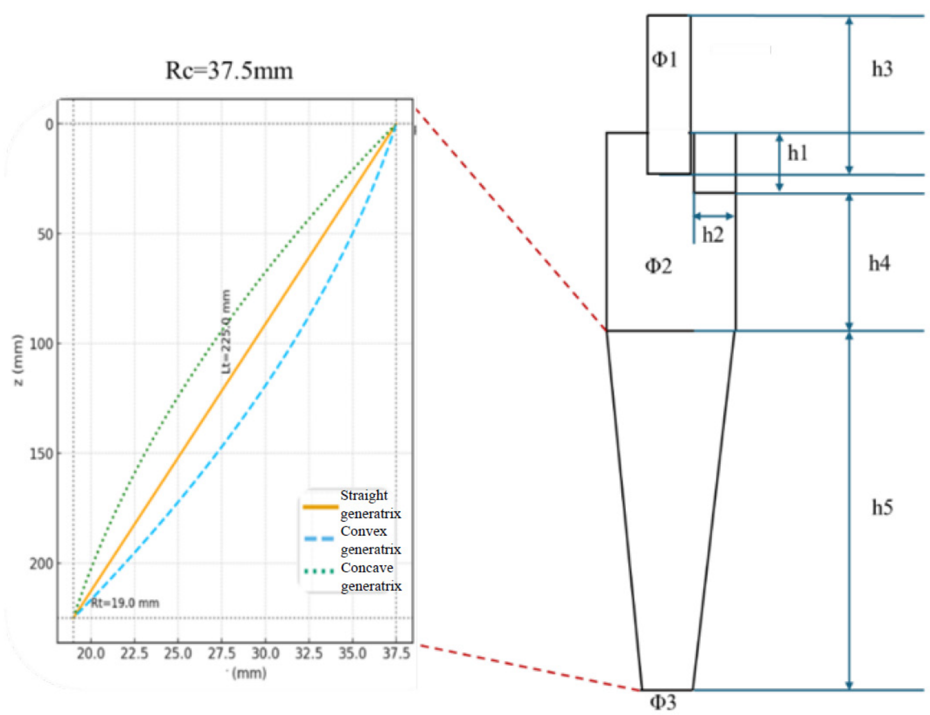

Figure 1. Schematic diagram of a cyclone separator.

3. Selection of CFD

Strong swirl and complex backflow occur in the internal flow of the cyclone separator, resulting in turbulence anisotropy, which influences the gas-solid separation efficiency. The traditional two-equation turbulence model has limitations in predicting strong swirl and strong curvature flow, and it is difficult to reflect the non-uniform turbulence characteristics in the separator.

Through the solution of the equations for Reynolds stress transport, the Reynolds Stress Model (RSM) incorporates the presence of anisotropic stresses and rotation, thus allowing for a more accurate representation of phenomena like the recirculation core in the separator. Several studies have proven that the RSM is better than the two-equation models when it comes to modeling the pressure drop behavior of the separator, making it one of the commonly used methods for numerical simulation of cyclonic separation.

$$\frac{\partial}{\partial_t}(\rho\overline{u_i u_j}) + \frac{\partial}{\partial x_k}(\rho U_k \overline{u_i u_j}) = D_{ij}^T + D_{ij}^L + P_{ij} + G_{ij} + \Phi_{ij} + \varepsilon_{ij} + F_{ij} \tag{8}$$

In the simulation of gas-solid two-phase flows, because of the disparity in scale between the particle phase and the gas phase, the Discrete Phase Model (DPM) is usually adopted in combined calculations to make a compromise between calculation efficiency and accuracy. In this way, the Eulerian method is adopted for solving the flow field of the continuous phase, while the Lagrangian method is adopted for calculating the trajectories of the particles, which can consider a variety of forces. For fine particles, DPM can quantitatively analyze their behavior within a swirl flow field. Combined with the high-precision turbulent flow field provided by RSM, it provides a basis for the optimization and evaluation of separators.

Coupling RSM with DPM makes it possible to numerically uncover the flow structure and particle separation mechanisms inside a cyclone separator. RSM provides an accurate simulation of the flow field, while DPM enables visualization and quantification of particle behavior. Used together, they offset the shortcomings of single turbulence models, supporting structural optimization and design, and form the core technical approach for investigating the air purification performance of separators.

In the simulation, the inlet boundary is set as a velocity inlet with v = 10 ms^{-1}, and the overflow and bottom outlets are set as flow outlets, with a diversion ratio of 20%. The pressure is discretized using the PRESTO scheme, while the pressure–velocity coupling is modeled using the SIMPLE algorithm, and the other governing equations are discretized using the QUICK scheme. The convergence criterion for the calculation is set at 1.0×10^{-5}.

4. Analysis of results

4.1. Particle trajectory plots

A comparison of the particle trajectories shows that the residence time and the distribution of motion paths are strongly influenced by particle size. The 0.5 μm fine particles, with their extremely low inertia, are highly susceptible to disturbances within the flow field. Their trajectories take the form of intricate spiral patterns, accompanied by a substantially prolonged residence time inside the chamber, with some values reaching close to 0.45 s. These particles exhibit pronounced flow-following and retention behavior, making them especially conducive to mass transfer and turbulence enhancement. Conversely, the 3 μm particles, owing to higher inertia, show poor flow-following behavior; the trajectory spread is narrow, and their residence time is lower (generally around 0.1 and 0.25 s). The rotating flow of these particles shows a spiral expansion nature; however, the radial diffusion distance is lower. In the case of 8 μm particles, the effect of inertia is dominant. The trajectories of such particles generally take the shape of regular spirals and do not respond to any small disturbances in the flow field. They have the lowest residence time (generally below 0.1 s) and move fast through the flow field. Overall, as particle size increases, particle flow-following behavior weakens, residence time shortens, and the effects of inertia and straight-through characteristics are enhanced. (**Figure 2–4**)

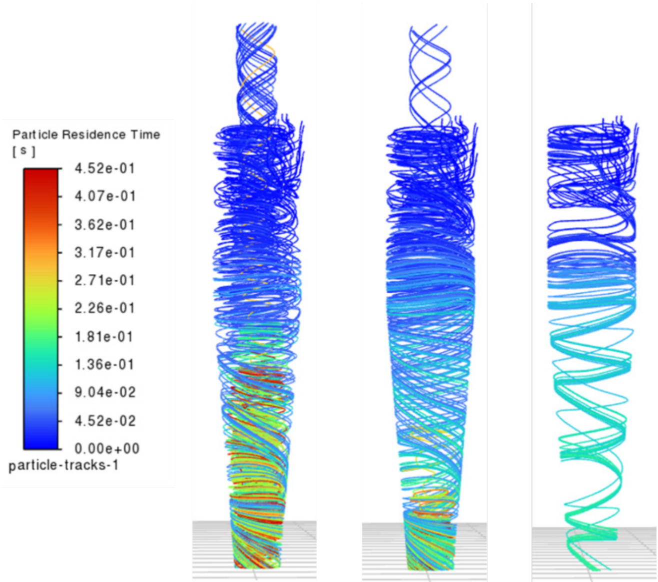

Figure 2. Particle trajectory plots for a straight-profile cyclone separator (left: 0.5 μm; middle: 3 μm; right: 8 μm).

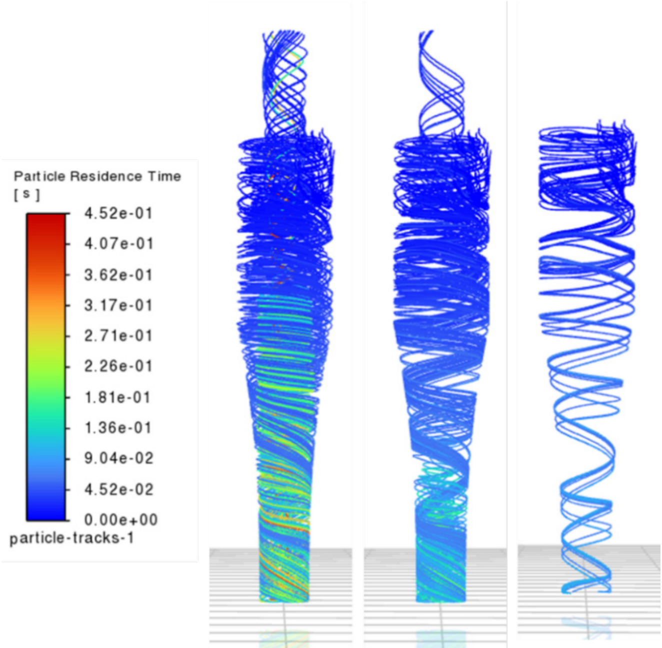

Figure 3. Trajectory diagrams for a convex-profile cyclone separator (left: 0.5 μm; middle: 3 μm; right: 8 μm).

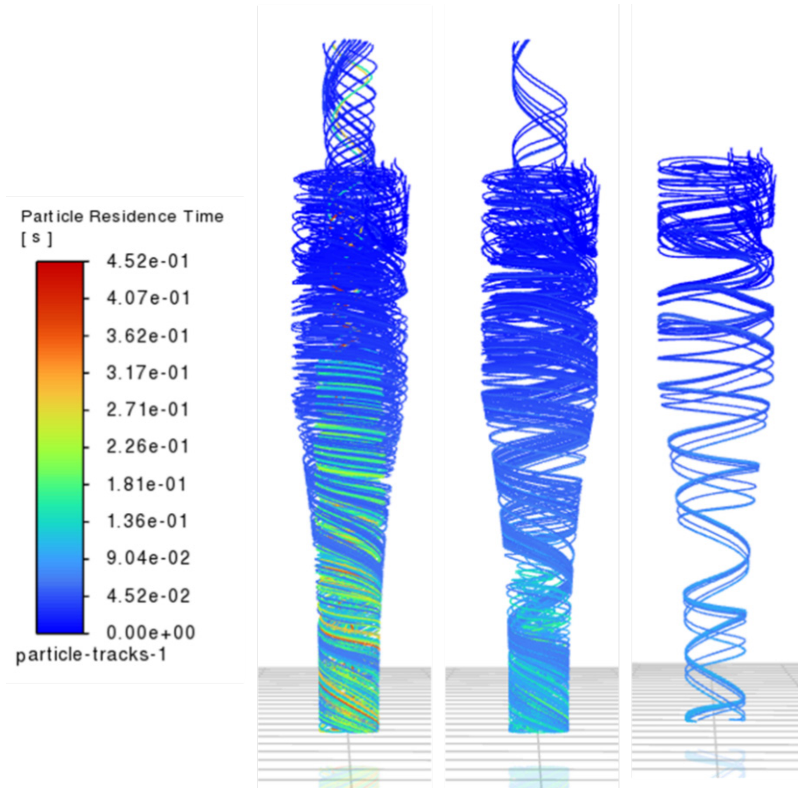

Figure 4. Trajectory diagrams for a concave-profile cyclone separator (left: 0.5 μm; middle: 3 μm, right: 8 μm).

The distribution of particle trajectories shows that particle size plays an important role in the residence characteristics of particles inside the cyclone separator. The trajectory of 0.5 μm fine particles is complicated, with multiple cycles, and the residence time is about 0.45 seconds, depending on the disturbance of the flow field. The trajectory of 3 μm particles is regular with a residence time of 0.1–0.2 seconds, which is a trade-off between flow-following and inertia. 8 μm particles are controlled by inertia, and most of their residence times are less than 0.1 second with straight-through trajectories. With the increase in particle size, the motion changes from flow-following to inertia-controlled, which reveals the classification effect of the cyclone separator for particles of different sizes, that is, retaining and mixing of small particles while separating large particles.

The characteristics of particle entrainment in the three cyclones are compared. The entrainment of 0.5 μm small particles in the straight cyclone is intensive and long-term; at the same time, the inhomogeneous particle distribution is likely to create non-uniformity of flow and high energy losses. On the other hand, the two other cyclone separators perform better both in terms of particle separation and flow stability. In the convex separator, there appears a localized region of intensive particle entrainment that reduces the losses due to turbulence, and the particle trajectories for medium-sized and large particles become regular. The concave cyclone separator further strengthens this trend; that is, the separation effect is more controllable, and additional loss is avoided.

4.2. Grade efficiency

The data in the table above indicate that the convex-generatrix cyclone offers higher overall efficiency than the other two cyclone separators. Within the fine particle size interval (0.5–3 μm), the separation efficiency of the convex-generatrix design is substantially greater than that achieved with the straight and concave generatrixes. For 2 μm particles, the convex cyclone separator reaches an efficiency of 0.746, compared with 0.63 for the straight and 0.638 for the concave configurations. At 3 μm, the efficiency of the convex cyclone climbs to 0.766, again surpassing the other two designs. These results provide clear evidence that the convex geometry brings a notable advantage in fine-particle capture and separation performance.

As particle size increases (≥ 5 μm), the grade efficiencies of the three cyclone profiles gradually converge toward 1, and the performance gap between them becomes negligible. In the low-to-medium size range, the convex-generatrix cyclone stands out as the most capable for fine-particle separation. The straight profile shows a modest edge for particle sizes around 3–4 μm, while the concave cyclone delivers a relatively balanced efficiency across the measured range, though it consistently falls short of the grade efficiency levels reached by the convex profile. See **Table 3**.

Table 3. Grade efficiency of cyclone separators

Particle size	Type of cyclone separator		
	Convex-generatrix cyclone separator	**Straight cyclone separator**	**Concave-generatrix cyclone separator**
0.5 μm	0.6	0.567	0.446
1 μm	0.567	0.5	0.574
1.5 μm	0.567	0.63	0.638
2 μm	0.746	0.633	0.638
3 μm	0.766	0.833	0.83
4 μm	0.9	0.89	0.829
5 μm	1	0.90	0.914
6 μm	1	1	1
7 μm	1	1	1
8 μm	1	1	1

4.3. Cloud chart analysis

4.3.1. Static pressure analysis

The static pressure distributions of the three cyclone separators are compared below. The straight profile creates a distinct low-pressure zone. A strong negative pressure core develops locally upstream with pressure close to -1200, driving flow separation and recirculation together with unstable vortex motion, all of which degrade system stability and efficiency. The convex section has a more consistent pressure distribution pattern, where the number of low-pressure areas decreases, and there are no extremely low-pressure cores; the flow becomes consistent, and there are minimal losses of energy. The concave section shows an increase in pressure distribution near the wall, where a high-pressure region develops on the edge, while the low pressure in the center of the duct decreases and approaches zero. Nevertheless, the presence of the high wall pressure makes the load greater, hence higher requirements for the engineering materials used. Generally, the profile that gives the best performance by minimizing vortex core under low pressures and ensuring uniform pressure distribution is the convex one; however, the straight and concave profiles have the risks of flow instability and high loads, respectively. See **Figure 5**.

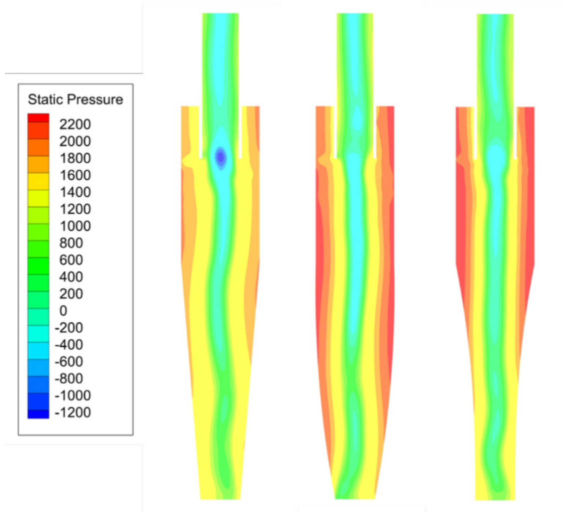

Figure 5. Static pressure contour map of a cyclone separator.

4.3.2. Tangential velocity

Tangential velocity comparisons show that all three cyclone separators develop significant swirl structures downstream of the inlet, differing in both intensity and distribution. The straight-profile separator generates a typical symmetrical rotating core together with a central counter-rotating flow, which results in high swirl intensity. The convex profile, on the other hand, exhibits a more vigorous rotational structure characterized by extensive and asymmetrical red zones of high tangential velocity. Here, the central counter-rotating flow spreads over the widest area, leading to increased flow instability. By contrast, the concave cyclone displays reduced vorticity intensity, a shrunken counter-rotational region, and rapid downstream vorticity decay, all of which yield a more stable flow. Overall, the convex cyclone reaches the highest rotational intensity at the cost of stability, whereas the concave cyclone lowers rotational energy while improving both flow uniformity and stability. See **Figure 6**.

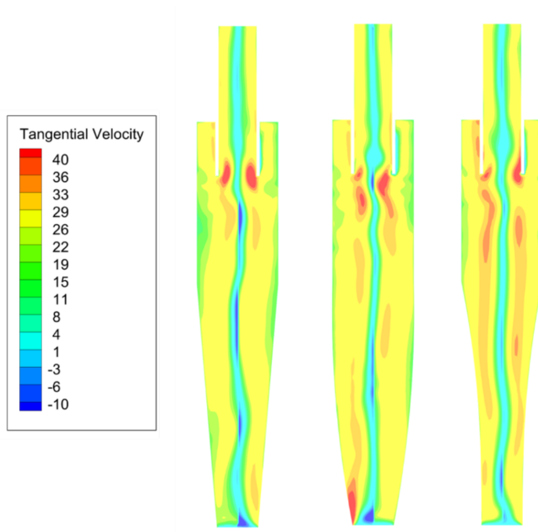

Figure 6. Tangential velocity contour plot of the cyclone separator.

4.3.3. Axial velocity

Axial velocity profiles for all three cyclone separators show typical features of central high-velocity jets, although differences are seen in terms of intensity and diffusion. For the left-side profile, the jet core is compact, energy is well preserved at a long distance, and there is good axial momentum transfer capability. But the problem with low recirculation in the boundary region may cause instability in the flow regime. In the case of a convex cyclone separator, there is a reduction in the size of high-velocity jets and rapid decay in velocity downstream, which shows greater diffusion of momentum and improved flow field uniformity. In the case of a concave cyclone separator, the high-velocity jets have smaller sizes and certain intensity is maintained downstream. However, the recirculation structures are considerably large, suggesting that this profile is linked to greater flow instability. The convex profile proves more favorable for jet diffusion and flow uniformity, whereas the straight profile tends to preserve energy efficiently, and the concave profile is characterized by recirculation instability. See **Figure 7**.

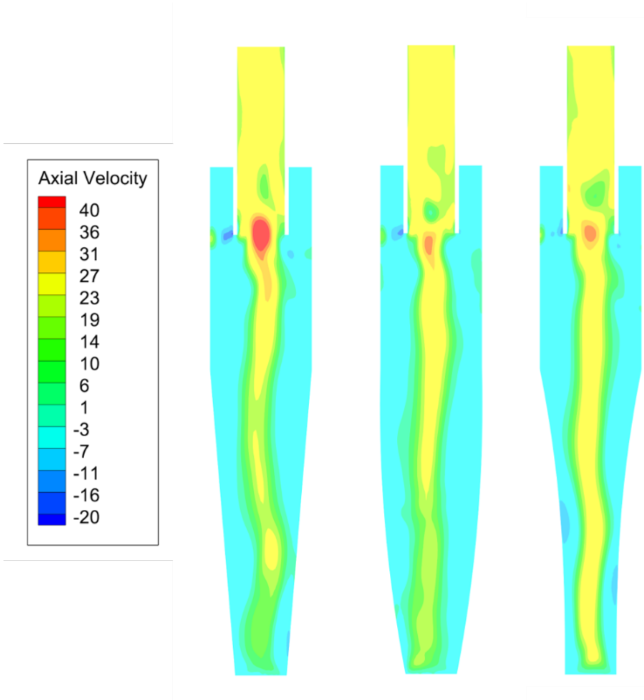

Figure 7. Axial velocity contour plot of cyclone separators.

4.3.4. Radial velocity

Downstream of the inlet, the radial velocity fields of the three cyclone separators all exhibit alternating positive and negative banded structures within the shear layer, though these bands differ notably in amplitude and spatial extent. The straight cyclone separator keeps radial velocity magnitudes at their lowest and restricts lateral momentum transport, producing a strong axial jet core. The convex cyclone separator, in contrast, generates intermediate radial velocity bands that are more continuous and symmetric, indicative of enhanced shear layer growth and entrainment, which act to expand the core region and foster downstream mixing. The concave cyclone separator exhibits the strongest and most asymmetrical radial motion, with radial velocity bands that extend toward the wall and retain high intensity downstream. This reflects more vigorous transverse momentum transport and three-dimensional effects, but it also signals greater flow instability and potentially higher wall loads. In summary, the convex cyclone separator strikes a better balance between mixing efficiency and flow stability, while the straight and concave profile lean towards extreme stability and mixing capabilities, respectively. See **Figure 8**.

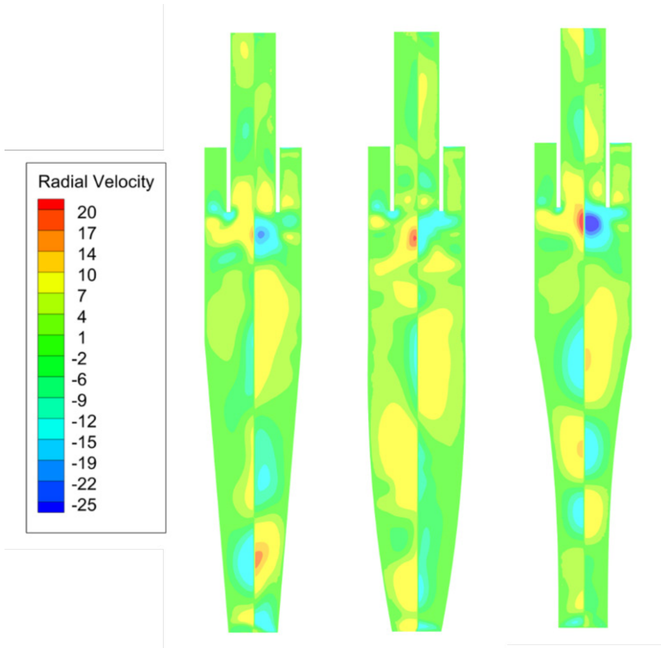

Figure 8. Radial velocity contour plot of cyclone separators.

5. Conclusion

In this work, a systematic set of CFD simulations is conducted to evaluate how three different curved conical sections, straight, concave, and convex, affect the air purification performance of cyclone separators. The data point to geometric curvature as a decisive factor in separation outcomes. The highest PM2.5 collection is seen with the convex profile, where the grade efficiency peaks at 82.4%, and the cut-off particle size drops to 2.1 μm, clearly outstripping the other two geometries. The concave profile, in contrast, stands out for its superior pressure drop characteristics and energy efficiency, while the straight profile yields results that lie between these two extremes. The motion of particles is strongly shaped by the flow field structure. Fine particles gain from extended residence time and stronger entrainment inside the convex shape, which makes them much easier to capture. Medium and coarse particles, on the other hand, follow relatively orderly trajectories in both convex and concave geometries so that they can be separated without difficulty. The three geometries also differ markedly in flow stability and energy utilization. The convex profile can keep the flow field reasonably uniform while achieving high collection efficiency, yet it also supports unstable vortices. The concave profile tends to dampen recirculation and shrink the low-pressure core, though this comes at the price of elevated wall pressure.

In general, the convex profile is a better choice for tasks that couple efficient fine-particle capture with high classification uniformity, whereas the concave profile is better suited to applications where low energy consumption and rapid separation take priority. By clarifying the ways in which a curved conical section modifies the flow field and redistributes particles, this study supplies both theoretical understanding and numerical evidence for the development of indoor air purification devices. Subsequent research can bring in experimental validation and intelligent optimization algorithms to strengthen the model's applicability and promote its transition into engineering practice.

Disclosure statement

The authors declare no conflict of interest.

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