Effect of External Cyclone Diameter on Performance of a Two-Stage Cyclone Separator

Jihe Chen,†‡ Bin Yang,*,‡† Zhong-an Jiang,*,‡† and Yapeng Wang‡

†School of Civil and Resource Engineering, University of Science and Technology Beijing, No. 30 Xueyuan Road, Haidian District, Beijing 100083, China
*China Academy of Safety Science and Technology, No. 17, Huixin West Street, Chaoyang District, Beijing 100029, China

ABSTRACT: As a widely used separation device, a cyclone separator is especially important to improve its separation efficiency. In this paper, a new two-stage cyclone separator is designed and modeled by the Reynolds stress model. Under the premise of determining the diameter of the second-stage cyclone (D), the effects of five first-stage cyclone diameters (Du) on the performance of the two-stage cyclone are simulated. The performance of the single-stage cyclone separator is also obtained. The results show that Du has significant effects on the internal pressure field, flow field, and vortex core of the two-stage cyclone. Compared with the single-stage cyclone separator, the separation efficiency of the two-stage cyclone separator is significantly improved. When Du = 6D, the separation efficiency is improved by 15.5% compared with that of the single-stage cyclone. In addition, the two-stage cyclone separator can effectively reduce the Euler number.

1. INTRODUCTION

Since the advent of the first conical cyclone in the 1880s, scientists have conducted various studies on the flow field characteristics, structural form, and size ratio of cyclones to improve their performance.1−6

The airflow and particle motion in the cyclone are very complicated. To clarify the law of airflow and particle migration, scientists have used a variety of research methods, including four types:7 (1) Experimental analysis methods: Solero and Coghe8 used LDA to conduct an experimental study on the entire gas flow field in the cyclone separator and measured the movement of the gas flow from the inlet to the exhaust pipe in detail, to better understand the complex flow field of the cyclone separator and realize the CFD value. The verification of the simulation provides complete data. Yazdabadi et al., Zhang and Hui, and Balestin et al.9−11 used PIV technology to study the variation of the precessing vortex core (PVC) of the cyclone separator. It was found that the flow rate and the number of swirls all affected the size, shape, and position of the PVC and the eddy current due to the inclination and bending of the PVC to the wall of the cyclone separator. The component of the vector is perpendicular to the longitudinal section of the cyclone. (2) Theoretical experience formula method: Karagöz and Avci12 proposed a mathematical model that can predict the pressure drop of a tangential inlet cyclone. Chen and Shi13 proposed a general model for calculating the pressure drop of a cyclone separator. However, due to the different types of cyclone separators, various assumptions exist, resulting in large differences in the results of various empirical formulas. Although the theoretical experience formula is simple and convenient, the accuracy is insufficient. (3) Statistical analysis methods: The models proposed by Casal and Martinez-Benet14 and Dirgo15 were developed by multiple regression analysis of larger pressure drop data sets based on different cyclone configurations. Although the statistical model is more convenient for predicting cyclone pressure drop, it is much more difficult to determine the most appropriate correlation function for fitting experimental data in this method, especially the limited computer statistical software and robust algorithms available at the time. (4) CFD numerical simulation method: Juengcharoensuksying et al.16 studied the influence of the cyclone and inlet angle on separation performance. Su et al.17 studied the influence of the exhaust mode on the turbulence characteristics of the separator. Zhang et al.18 designed a new hexagonal cyclone separator and optimized it. Some scientists1,19−21 used algorithms to optimize the parameters of the cyclone separator to get the best parameters of the separator, and some scientists22,23 used electric and magnetic fields to improve the separation efficiency of the cyclone separator. Although each research method of the cyclone can realize the design and optimization of the cyclone separator, the advantages of the CFD numerical simulation method are more obvious, not only the parameters can be changed quickly but also the pressure field, the flow field, and the vortex core can be expressed relatively intuitively.

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However, with the need for more and more fine particles, the single-stage cyclone has been unable to meet the requirements, and the two-stage cyclone and even multistage cyclone have emerged. In this paper, the effect of the external cyclone diameter ($D_u$) on the performance of a new two-stage cyclone separator is studied. This paper uses the combination of experimental analysis and CFD numerical simulation to study the effect of $D_u$ on the performance of a two-stage cyclone separator. The first-stage cyclone separator has high separation efficiency for large particles and can effectively reduce the load of the second-stage cyclone separator; the second-stage cyclone has high separation efficiency for small particles and can effectively separate small particles to make up for the deficiency of the first-stage cyclone. If $D_u$ is too small, the inside of the first-stage cyclone is too narrow to form an unobstructed airflow path that moves from the first-stage cyclone floor to the second-stage cyclone inlet; if $D_u$ is too large, the two-stage cyclone will be too bulky. Therefore, in the case of a fixed second-stage cyclone diameter, it is necessary to study the effect of $D_u$ on the

Figure 1. Comparison of experimental values and simulated values: (a) Pressure drop and (b) efficiency.

Figure 2. Measurement point arrangement of internal flow field and concentration field experiment verification: (a) measuring point arrangement, (b) volume concentration distribution, (c) first-stage cyclone spiral, (d) comparison of simulated and experimental particle concentrations, and (e) comparison of simulated and experimental velocity.
performance of the two-stage cyclone separator. By analyzing the internal pressure field, flow field, vortex core, Euler number, Stokes number, etc. of the two-stage cyclone separator, the effect of Du on the performance of the two-stage cyclone separator is obtained.

2. RESULTS AND DISCUSSION

2.1. Simulation Result Verification and Discussion. Pressure drop and separation efficiency are the two most important indicators of the cyclone. Figure 1 is a comparison of experimental and simulation values. The solid line indicates the simulation value, and the broken line indicates the experimental value. When Du = 1D, it means a single-stage cyclone separator. It is found that the pressure drop experimental results are similar to the simulation results, and the error is within 2.5%. The simulation value of the separation efficiency is basically consistent with the variation of the experimental value, and the error is within 5.6%. Since the first-stage cyclone inlet, the second-stage cyclone inlet, and the second-stage cyclone outlet area are different, the pressure drop is represented by the difference in total pressure. The following formula is used to calculate separation efficiency

\[ \eta = \left( 1 - \frac{C_2}{C_1} \right) \times 100\% \]  

where \( \eta \) is the efficiency, \( C_1 \) is the inlet particle concentration, and \( C_2 \) is the export particle concentration.

It can be seen from Figure 1a that the first-stage cyclone pressure drop is much smaller than the second-stage cyclone. The pressure drop caused by the second-stage cyclone is dominant, and the pressure drop caused by the first-stage cyclone is secondary. Compared to a single-stage cyclone, the pressure drop of the two-stage cyclone is greatly increased. As Du increases, the first-stage cyclone pressure drop gradually increases, but when Du = 6D, the first-stage cyclone pressure drop is reduced, which is an interesting thing. As Du increases, the second-stage cyclone and the two-stage cyclone pressure drop gradually decrease, and a local maximum in pressure drop is observed at Du = 4D, which is also an interesting observation.

It can be seen from Figure 1b that the total separation efficiency of the two-stage cyclone separator is larger than that of the single-stage cyclone. As Du increases, the total efficiency of the two-stage cyclone gradually increases. When Du = 6D, the separation efficiency of the two-stage cyclone is 15.5% higher than that of the single-stage cyclone. When Du increases from 2D to 6D, the first-stage cyclone separation efficiency increased from 34.9 to 96.1%, an increase of 91.2%. When Du is greater than 4D, the total efficiency is greater than 99%, and as Du increases, the total efficiency does not increase significantly. Therefore, if a two-stage cyclone is designed, to ensure a high total separation efficiency, the external cyclone diameter should be at least four times the internal cyclone diameter.

The test points for testing the internal flow field and concentration field of the cyclone are the same, and the arrangement of the measuring points and the test results is shown in Figure 2.

Figure 2a shows the arrangement of the internal flow field and the concentration field measurement point, which is the \( z = 0 \) section. The first-stage cyclone is arranged with 10 measuring points with a measuring point spacing of 24 mm.

The second-stage cyclone is arranged with five measuring points with a measuring point spacing of 16 mm. Figure 2b shows a plot of the concentration distribution of the simulated body particles in the two-stage cyclone separator. It can be seen that there is a clear spiral on the inner wall of the first-stage cyclone, which is consistent with the experimental results observed in Figure 2c. It is also consistent with the results of other scholars.27

It can be seen from Figure 2d,e that the simulation results are in good agreement with the experimental results, indicating that the simulation results are reliable. Due to the complexity of the flow field inside the cyclone, errors are considered acceptable.

2.2. Effect of External Cyclone Diameter on Pressure Field and Flow Field. The pressure field and flow field can reveal the reasons for the variation of the two-stage cyclone pressure drop and separation efficiency. Numerical simulation can describe the internal pressure field and flow field of the cyclone in detail, which is unmatched by experiments. To quantitatively reveal the internal pressure field and flow field distribution of the two-stage cyclone separator, eight straight lines \( (y = -0.040\ m, y = -0.064\ m, y = -0.096\ m, y = -0.128\ m, y = -0.160\ m, y = -0.192\ m, y = -0.256\ m, and y = -0.288\ m) \) in the \( z = 0 \) section are selected as the research objects, and the static pressure, tangential velocity, and axial velocity along the x axis distribution are studied. Although \( y = -0.040\ m, y = -0.064\ m, and y = -0.096\ m \) three lines are in the cylinder part of the second-stage cyclone separator, which is called the cylinder straight line, \( y = -0.128\ m, y = -0.160\ m, and y = -0.192\ m \) three lines are in the vertebral body part of the second-stage cyclone separator, which is called the vertebral body straight line; the two lines of \( y = -0.256\ m \) and \( y = -0.288\ m \) are in the hopper part of the second-stage cyclone separator, which is called the hopper straight line, as shown in Figure 3.

![Figure 3](image-url)

**Figure 3.** Analysis lines at \( z = 0 \) section.

2.2.1. Effect of External Cyclone Diameter on Static Pressure. Due to the presence of the swirling airflow, the internal pressure drop problem of the cyclone becomes very complicated. Figure 4 shows the internal static pressure distribution of the two-stage cyclone separator at different Du’s. When Du ≥ 2D, with the increase of Du, the internal static pressure of the first-stage cyclone gradually increases from the inner wall of the first-stage cyclone to the outer wall of the second-stage cyclone. When Du = 2D, the falling gradient is the largest; when 3D ≤ Du ≤ 5 D, the difference of the descending gradient is small; when Du = 6D, the falling gradient is the smallest. Conversely, the internal static pressure drop gradient of the second-stage cyclone is not so regular. The order of the static pressure values at the \( z = 0 \) position is
Figure 4. Static pressure distribution: (a) $Y = -0.040$ m, (b) $Y = -0.064$ m, (c) $Y = -0.096$ m, (d) $Y = -0.128$ m, (e) $Y = -0.160$ m, (f) $Y = -0.192$ m, (g) $Y = -0.256$ m, and (h) $Y = -0.288$ m.
Figure 5. Tangential velocity: (a) \( Y = -0.040 \) m, (b) \( Y = -0.064 \) m, (c) \( Y = -0.096 \) m, (d) \( Y = -0.128 \) m, (e) \( Y = -0.160 \) m, (f) \( Y = -0.192 \) m, (g) \( Y = -0.256 \) m, and (h) \( Y = -0.288 \) m.
Figure 6. Axial velocity: (a) \( Y = -0.040 \) m, (b) \( Y = -0.064 \) m, (c) \( Y = -0.096 \) m, (d) \( Y = -0.128 \) m, (e) \( Y = -0.160 \) m, (f) \( Y = -0.192 \) m, (g) \( Y = -0.256 \) m, and (h) \( Y = -0.288 \) m.
2D < 4D < 3D < 5D < 6D. This law of variation is consistent with the simulation and experimental values of pressure drop. Static pressure is the main cause of pressure drop changes, and this can explain why 4D is an interesting observation. During the change of the external diameter from 3D–5D, the internal pressure field changes to some extent, resulting in a high pressure drop at 4D.

Regardless of the value of Du, the internal static pressure of the second-stage cyclone exhibits a "V"-shaped distribution along the x axis and a minimum at x = 0. This phenomenon is consistent with the principle of conservation of momentum. The principle of conservation of the momentum moment is also called the principle of conservation of angular momentum, which is a process of static pressure conversion to dynamic pressure. Because the first-stage cyclone has only the cylinder, there is no vertebral body and hopper, and the inlet velocity is also less than the second-stage cyclone; the second-stage cyclone pressure drop is much larger than the first-stage cyclone pressure drop. As shown in Figure 4c, when y = −0.096 m and Du = 2D, the static pressure value at x = 0 is −6972 Pa, which is 2.3 times that of Du = 1D (−3033 Pa) and 1.3 times that of Du = 6D (−5737 Pa). The first-stage cyclone static pressure is much smaller than the second-stage cyclone static pressure. This is consistent with the previous experimental and simulation values.

2.2.2. Effect of External Cyclone Diameter on Tangential Velocity. The tangential velocity is an important factor affecting the centrifugal force of the particles. Figure 5 shows the internal tangential velocity distribution of the two-stage cyclone separator at different Du’s. It can be seen that the velocity follows a symmetric distribution. In the cylinder portion, the tangential velocity at the first-stage cyclone wall is zero and increases to a maximum at 0.45D from the wall along the radial direction. It is then reduced again to zero at the second-stage cyclone wall and increases to a maximum along the radial direction at 0.14D from the wall. Due to the friction between the eddy current detector and the vortex core, the tangential velocity of the second-stage cyclone maximum to the center point is gradually reduced. The tangential velocity is well symmetric in the barrel portion and the vertebral portion. However, in the hopper part, since the vortex core is offset and is not at the same position as the geometric center, the tangential velocity symmetry is poor.

In the cylinder part and the hopper part, the change of Du has a great effect on the maximum value of the first-stage cyclone tangential velocity and has a little effect on the maximum value of the second-stage cyclone tangential velocity. As shown in Figure 5a, when y = −0.040 m and Du = 2D, the maximum tangential velocity of the first-stage cyclone is 44.8 m/s, which is 33% higher than the maximum value (30.0 m/s) of Du = 6D. At this time, the change of the maximum value of the first-stage cyclone tangential velocity is not obvious. The results of the vertebral body are just the opposite. The change of Du has a great effect on the maximum tangential velocity of the second-stage cyclone but has a little effect on the maximum tangential velocity of the first-stage cyclone. As shown in Figure 5c, when y = −0.040 m and Du = 2D, the maximum tangential velocity of the second-stage cyclone is 38.5 m/s, which is 30% larger than the maximum value of Du = 6D (27.1 m/s). At this time, the change of the maximum value of the first-stage cyclone tangential velocity is relatively insignificant.

As Du increases, the maximum velocity of the first-stage cyclone gradually decreases. Theoretically, as the first-stage cyclone increases with Du, the separation efficiency gradually decreases. However, according to the simulation and experimental values, as the Du increases, the first-stage cyclone separation efficiency gradually increases. The reason for this may be that as the Du increases, the axial velocity decreases gradually at the bottom of the first-stage cyclone. The possibility of particle deposition at the bottom of the first-stage cyclone gradually increases, resulting in a gradual increase in the efficiency of the first-stage cyclone separation.

2.2.3. Effect of External Cyclone Diameter on Axial Velocity. The axial velocity is an important factor in the residence time of the particles in the cyclone. Figure 6 shows the internal axial velocity distribution of the two-stage cyclone separator at different Du’s. It can be seen that since the first-stage cyclone has only one inlet in the positive direction of the x axis, the internal axial velocity of the first-stage cyclone is not completely symmetric with respect to x = 0, and the first-stage cyclone is partially negative x axis. The axial velocity of the direction is significantly larger than the positive direction of the x axis. This velocity structure promotes the deposition of particles on the substrate. With the increase of Du, the axial velocity change of the first-stage cyclone gradually becomes slower, which is beneficial to reduce the phenomenon of particle entrainment. Since the second-stage cyclone has two inlets, the axial velocity is completely symmetrical in the axial direction of the second-stage cyclone, presenting a perfect "W" shape.

In the vertebral body part, when Du = 2D and 4D, the axial velocity of the second-stage cyclone at x = 0 is large, indicating that the suction force at this time is large, which is favorable for the gas discharge after purification.

In the hopper part, when Du = 1D, the axial velocity at x = 0 is the largest, which will cause the particles deposited in the hopper to be re-entrained, reducing the separation efficiency. This is also an important reason why the separation efficiency of the two-stage cyclone separator is greater than that of the single-stage cyclone separator. As Du increases, the axial velocity at the bottom of the first-stage cyclone is sorted from large to small at x = 0 to 2D > 3D > 4D > 5D > 6D. This is in complete agreement with the guess mentioned above. The bottom axial velocity is an important factor affecting the cyclone separation efficiency.

2.3. Effect of External Cyclone Diameter on Vortex Core. There are many ways to identify vortex core, and the most basic of which is based on the identification of velocity gradient tensors. The criteria for identifying the vortex core based on the velocity gradient tensor are Q-criterion, Δ-criterion, λ2-criterion, swirling strength criterion, enhanced swirling strength criterion, and triple decomposition. Of these several criteria, Q-criterion is the most widely used. The Q-criterion is the second invariant of the velocity gradient tensor, which defines a vortex as a "connected fluid region with a positive second invariant of Vu". For a region with positive values, it could include regions with negative discriminants and exclude regions with positive discriminants.

Figures 7 and 8 show the vortex core region based on the Q-criterion (level set to 0.04, 0.08, and colored with velocity magnitude) for the first-stage cyclone and second-stage cyclone, respectively. As can be seen from Figure 7, as the change of Du, the first-stage cyclone vortex core changes significantly. When Du = 2D, the vortex core completely surrounds the second-stage cyclone, and the vortex core region is a circle around the central axis. When Du = 3D, the vortex...
core around the outer wall of the second-stage cyclone is distorted, and the “S” shape is formed in the vertebral body part and the hopper part, which is not conducive to the separation of the particles. When Du = 4D, the lower vortex core of the first-stage cyclone separator appears to be tail swinging, but it is obviously larger than the normal pendulum tail. With the increase of Du, the volume of the first-stage cyclone increases, and the tangential velocity of the vortex core region decreases significantly, causing the vortex core region around the inner wall of the primary cyclone separator and the outer wall of the second-stage cyclone to gradually decrease. There is obvious deformation or even fracture on the surface of the vortex core, which will cause energy attenuation.

It can be seen from Figure 8 that since the gas flow rate is constant, when Du ≥ 2D, the gas flow rate entering the second-stage cyclone does not substantially change, and only the pressure affects the vortex core, so the change of the second-stage cyclone vortex core is not obvious.

2.4. Effect of External Cyclone Diameter on Particle Separation Efficiency. The separation efficiency is an important parameter to describe the performance of the cyclone separator. In addition to the overall separation efficiency, the performance of the cyclone can also be expressed by the cut size and maximum size of the particles. There are two ways to express the cut size and the maximum size: one is expressed in micrometer, and the other is expressed in the Stokes number. The Stokes number based on the cut size and the maximum size can be expressed as

\[
\text{Stk}_{\text{mean}} = \frac{d_{\text{mean}}^2 \rho_p V_{\text{in}}}{18 \mu D_{\text{in}}}
\]

(2)

\[
\text{Stk}_{\text{max}} = \frac{d_{\text{max}}^2 \rho_p V_{\text{in}}}{18 \mu D_{\text{in}}}
\]

(3)

where \(d_{\text{mean}}\) is the particle cut size, \(d_{\text{max}}\) is the particle maximum size, \(\rho_p\) is the particle density, \(V_{\text{in}}\) is the inlet velocity, \(\mu\) is the gas viscosity, and \(D_{\text{in}}\) is the inlet equivalent diameter.
As can be seen from Figure 9, the variation law of the cyclone Stokes number with Du is consistent with the variation law of the cyclone efficiency. The Stokes number is the characteristic response time of the fluid divided by the characteristic response time of the particle. If the Stokes number is small that is much less than 1, it means that the particle motion is tightly coupled to the fluid motion that is the particle dispersal is the same as the fluid dispersal. If the Stokes number is large, the particles are not influence by the fluid—their response time is longer than the time that the fluid has to act on it, and so the particle will pass through the flow without much deflection in its initial trajectory. Therefore, the Stokes number as a dimensionless parameter can reflect the cyclone separation efficiency to some extent. The larger the Stokes number, the higher the separation efficiency. As can be seen from Figure 9a, as Du increases, the Stokes number gradually increases, and the separation efficiency also increases.

#### 2.5. Effect of External Cyclone Diameter on Pressure Drop

Another important parameter describing the performance of a cyclone is the pressure drop, which can be expressed in terms of the dimensionless parameter Euler number \((Eu)\).\(^{36,37}\) The Euler number expression is

\[
Eu = \frac{\Delta P}{0.5 \rho V_{in}^2}
\]

As can be seen from Figure 10, the variation law of the cyclone Euler number with Du is consistent with the variation law of the cyclone pressure drop. When Du = 6D, the two-stage cyclone Euler number is reduced by 51.2% compared to the single-stage cyclone. When the fluid velocity is constant, the Euler number is consistent with the pressure drop because the Euler number is a dimensionless parameter that characterizes the relationship between fluid pressure drop and fluid kinetic energy.

### 3. CONCLUSIONS

This paper presents a new two-stage cyclone separator. Based on the experimental research, the effect of external cyclone diameter Du on the performance of the two-stage cyclone separator is studied by CFD simulation. The main conclusions are as follows:

1. The external cyclone diameter Du has a significant effect on the pressure field, flow field, and vortex core of the two-stage cyclone, and the effect on the first-stage cyclone is significantly more significant than that of the second-stage cyclone.
2. The two-stage cyclone separator has higher separation efficiency than the single-stage cyclone separator. Also, with the increase of Du, the separation efficiency of the two-stage cyclone gradually increases. When Du ≥ 4D, the separation efficiency of the two-stage cyclone is greater than 99%.
3. The variation law of the cyclone Stokes number with Du is consistent with the variation law of the cyclone efficiency. Also, the variation law of the cyclone Euler number with Du is consistent with the variation law of the cyclone pressure drop. Compared with the single-stage cyclone, the Euler number of the two-stage cyclone can be reduced by 51.2%.

### 4. EXPERIMENTAL SECTION AND COMPUTATIONAL METHODS

#### 4.1. Experimental Schematic

The experimental schematic and geometric design of the two-stage cyclone separator are shown in Figure 11. The test bench and method used are the same as described in the previous work,\(^{27}\) and the particle counter used is a portable particle counter (AeroTrakTM TSI 9306-V) for determining the number of particles in the...
upstream and downstream. The experimental results show that the particle size distribution and cumulative distribution of talc powder are shown in Figure 12. The distribution index is 2.42, and the median is 1.73 μm. When $Du = 1D$, it means that there is only a second-stage cyclone separator, and there is no first-stage cyclone separator.

To verify the accuracy of the simulation results from the internal flow field and the particle concentration field, we use the DUSTTRAK DRX Aerosol Monitor 8530 and the Kanomax Multichannel Anemomaster System 6243 to measure the gas velocity and particle concentration, respectively, as shown in Figure 13.

The Kanomax Multichannel Anemomaster System 6243 can form a multichannel system while accurately and quickly measuring multipoint wind speed values. The DUSTTRAK DRX Aerosol Monitor 8530 provides real-time aerosol mass concentration readings by gravity sampling, but the instrument has a disadvantage that the maximum range is only 400 mg/m³. Due to the high internal particle concentration of the first-stage cyclone, when we measured the internal particle concentration of the first-stage cyclone, it was found that the concentration on the $y = -0.096$ m measuring point exceeded the maximum range of the DUSTTRAK DRX Aerosol Monitor 8530, resulting in the instrument to malfunction, so we only measured the particle concentration field in the

![Figure 11](image1.png)

**Figure 11.** Experimental diagram and parameters of the two-stage cyclone separator: (a) experimental diagram, (b) geometric model, (c) geometric parameters, and (d) dimensions. 01: particle feeder, 02: Pitot tube, 03: pressure probe, 04: partial counter, 05: concentration meter, 06: fan, 07: filter, 08: two-stage cyclone, 09: second-stage cyclone, 10: first-stage cyclone, and 11: hopper.

![Figure 12](image2.png)

**Figure 12.** Talc particle size distribution and cumulative distribution.
second-stage cyclone. We selected Du = 4D to test the internal flow field and concentration field of the cyclone using the Kanomax Multichannel Anemomaster System 6243 and DUSTTRAK DRX Aerosol Monitor 8530.

4.2. Mathematical Model. Because the concentration of talc at the inlet is small, the volume fraction is much less than 10%, and the effect of the particles on gas migration can be ignored. Assuming that the talc is a discrete phase, and the gas is a continuous phase, the Euler–Lagrangian method is used to simulate the two-phase flow.

For steady and incompressible fluid flow in cyclone separators, the Reynolds-averaged Navier–Stokes (RANS) equation is expressed as follows:

$$\frac{\partial \bar{u}_i}{\partial x_j} = \frac{\partial \bar{p}}{\partial x_i} + \rho \left( \frac{\partial \bar{u}_j}{\partial x_i} + \frac{\partial \bar{u}_i}{\partial x_j} - \rho \bar{u}_i \bar{u}_j \right) - \rho \bar{u}_i \bar{u}_j$$

(5)

The left hand side of this equation represents the change in mean momentum of the fluid element owing to the unsteadiness in the mean flow and the convection by the mean flow. This change is balanced by the mean body force, the viscous stresses, and the apparent stress (−ρu_i u_j) owing to the fluctuating velocity field, generally referred to as the Reynolds stress.

Because the Reynolds stress model (RSM) considers the effects of streamline curvature, eddy current, rotation, and the rapid change of the strain rate in a more rigorous manner than single equation and two-equation models, it can give accurate prediction results for complex flows. In this paper, the RSM is used as a closure model to solve the Reynolds stress tensor. The mathematical model is shown below:

$$\frac{\partial}{\partial t}(\rho \bar{u}_i \bar{u}_j) + \frac{\partial}{\partial x_k} \left( \rho U_k \bar{u}_i \bar{u}_j \right) = D_{\bar{u}_i} + \phi_{\bar{u}_i} + G_{\bar{u}_i} - \epsilon_{\bar{u}_i} + S$$

(6)

$$D_{\bar{u}_i} = - \frac{\partial}{\partial x_k} \left( \rho \bar{u}_i \bar{u}_j + \bar{u}_j \bar{u}_k \delta_{ik} + \bar{u}_k \bar{u}_i \delta_{jk} - \rho \frac{\partial \bar{u}_i}{\partial x_k} \right)$$

(7)

$$\phi_{\bar{u}_i} = \rho \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

(8)

$$G_{\bar{u}_i} = \rho \left( \frac{\partial U_j}{\partial x_k} + \frac{\partial U_k}{\partial x_j} \right)$$

(9)

$$\epsilon_{\bar{u}_i} = 2\rho \frac{\partial u_i}{\partial x_k} \frac{\partial u_k}{\partial x_i}$$

(10)

where i, j, and k are the three directions in the Cartesian coordinate system; D_{\bar{u}_i}, \phi_{\bar{u}_i}, G_{\bar{u}_i}, and S represent the diffusion term, the pressure strain term, the production term, the dissipation term, and the user-defined source term, respectively; u_i, u_j, and u_k represent the velocity fluctuations.

After the continuous phase is stabilized, the discrete phase is injected from the inlet by the DPM method. ANSYS Fluent predicts the trajectory of a discrete phase particle by integrating the force balance on the particle, which is written in a Lagrangian reference frame. This force balance equates the particle inertia with the forces acting on the particle and can be written as:

$$m_p \frac{d\mathbf{u}_p}{dt} = m_p \left( \frac{\mu - \rho}{\tau_p} \right) + m_p \frac{g(\rho_p - \rho)}{\rho_p} + F$$

(11)

where m_p is the particle mass, \mu is the fluid phase velocity, \mu_p is the particle velocity, \rho is the fluid density, \rho_p is the density of the particle, F is an additional force, m_p \left( \frac{\mu - \rho}{\tau_p} \right) is the drag force, and \tau_p is the particle relaxation time calculated by

$$\tau_p = \frac{\rho_p d_p^2}{18\mu C_d Re}$$

(12)

where \mu is the molecular viscosity of the fluid, d_p is the particle diameter, and Re is the relative Reynolds number.

A random tracking model is used to predict the particle migration trajectory. The random tracking model does not depend on the shape of the mesh and is very suitable for unstructured meshes by using random methods including the effects of instantaneous turbulent velocity fluctuations on particle trajectories.

Figure 13. Gas velocity and particle concentration test system: (a) DUSTTRAK DRX Aerosol Monitor 8530 and (b) Kanomax Multichannel Anemomaster System 6243.
4.3. Boundary Condition Settings. According to the experimental results, the simulation boundary conditions are set in Table 1.

4.4. Grid Independence Verification. The geometric parameters of the designed two-stage cyclone separator do not change except for the change of Du. As the external cyclone diameter increases, the number of mesh elements gradually increases. To verify grid independence, each Du needs to be verified. Also, simulations and experimental comparisons have also been added. The verification results are shown in the Table 2.

As can be seen from the Table 2, as the number of mesh elements increases, the pressure drop and separation efficiency change gradually. When mesh levels 1–4, the growth rate is higher. When mesh levels 4–5, the growth rate is lower. Considering the computer performance, mesh 4 is selected as the final computing grid.

Table 1. Boundary Condition Types and Settings

| type   | property   | value          | type   | property   | value          |
|--------|------------|----------------|--------|------------|----------------|
| general| solver type| pressure based | viscous| RSM        | linear pressure strain |
| time   | steady     |                | near-wall treatment | standard wall function |
| air    | density    | 1.225 kg/m³    | outlet | velocity inlet | −32 m/s |
|       | viscosity  | 1.79 × 10⁵ Pa·s| inlet  | pressure inlet | 0 Pa |
| inlet 1| boundary condition | interior | inlet 2| boundary condition | interior |
| particle| min diameter | 1.0 × 10⁷ μm  | particle| density | 2800 kg/m³ |
| max diameter  | 1.0 × 10⁷ μm  |              | inlet concentration | 1040 mg/m³ |
| mean diameter | 1.7 × 10⁶ μm  |              | spread parameter | 2.42 |

Table 2. Characteristics of the Grids

| Du     | characteristic parameter | mesh 1 | mesh 2 | mesh 3 | mesh 4 | mesh 5 | experiment |
|--------|--------------------------|--------|--------|--------|--------|--------|------------|
| 1D     | elements                 | 81451  | 126921 | 174872 | 214581 | 3047891| 2610       |
| 2D     | pressure drop simulation (Pa) | 2379  | 2415  | 2512  | 2546  | 2555  | 615784     |
|        | error (%)                | 8.85   | 7.47   | 3.75   | 2.45   | 2.11   |            |
| 3D     | separation efficiency simulation (%) | 77.4  | 79.8   | 83.1   | 84.4   | 84.7   | 80.0       |
|        | error (%)                | 3.25   | 0.25   | −3.87  | −5.50  | −5.88  |            |
| 4D     | pressure drop simulation (Pa) | 200348| 263571 | 392578 | 478165 | 61071 | 79.7       |
|        | error (%)                | 5899   | 5935   | 6010   | 6057   | 6071   |            |
| 5D     | separation efficiency simulation (%) | 78.4  | 79.7   | 81.0   | 81.7   | 81.9   |            |
|        | error (%)                | 1.63   | 0.00   | −1.63  | −2.51  | −2.76  |            |
| 6D     | pressure drop simulation (Pa) | 287957| 375982 | 548977 | 613584 | 824785 |            |
|        | error (%)                | 4937   | 4999   | 5080   | 5128   | 5155   |            |
|        | separation efficiency simulation (%) | 4.47  | 3.27   | 1.70   | 0.77   | 0.25   |            |
|        | error (%)                | 96.7   | 96.8   | 97.0   | 97.1   | 97.2   |            |
|        | error (%)                | 96.2   |        |        |        |        |            |
| 1E     | pressure drop simulation (Pa) | 422712| 587225 | 695001 | 805560 | 1024783|            |
|        | error (%)                | 5217   | 5291   | 5388   | 5492   | 5510   |            |
|        | separation efficiency simulation (%) | 6.54  | 5.21   | 3.48   | 1.61   | 1.29   |            |
|        | error (%)                | 97.6   | 98.4   | 98.7   | 99.4   | 99.6   |            |
|        | error (%)                | 98.6   |        |        |        |        |            |
| 2E     | pressure drop simulation (Pa) | 562578| 718554 | 991025 | 1135472| 1436981|            |
|        | error (%)                | 5018   | 5087   | 5122   | 5154   | 5161   |            |
|        | separation efficiency simulation (%) | 6.54  | 5.21   | 3.48   | 1.61   | 1.29   |            |
|        | error (%)                | 97.6   | 97.9   | 98.9   | 99.4   | 99.4   |            |
|        | error (%)                | 98.9   |        |        |        |        |            |
| 3E     | pressure drop simulation (Pa) | 682577| 892857 | 1136872| 1395002| 1685882|            |
|        | error (%)                | 4800   | 4869   | 4901   | 4917   | 4925   |            |
|        | separation efficiency simulation (%) | 3.75  | 2.37   | 1.72   | 1.40   | 1.24   |            |
|        | error (%)                | 99.6   | 99.8   | 99.9   | 99.9   | 99.9   |            |

4.3. Boundary Condition Settings. According to the experimental results, the simulation boundary conditions are set in Table 1.

4.4. Grid Independence Verification. The geometric parameters of the designed two-stage cyclone separator do not change except for the change of Du. As the external cyclone diameter increases, the number of mesh elements gradually increases. To verify grid independence, each Du needs to be verified. Also, simulations and experimental comparisons have also been added. The verification results are shown in the Table 2.

As can be seen from the Table 2, as the number of mesh elements increases, the pressure drop and separation efficiency change gradually. When mesh levels 1–4, the growth rate is higher. When mesh levels 4–5, the growth rate is lower. Considering the computer performance, mesh 4 is selected as the final computing grid.

**AUTHOR INFORMATION**

**Corresponding Authors**

*E-mail: yangb@chinasafety.ac.cn (B.Y.).
*E-mail: jiangzhongan@ustb.edu.cn (Z.J.).

**ORCID**

Jihe Chen: 0000-0001-9238-5806
Zhong-an Jiang: 0000-0001-9733-8662

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**NOMENCLATURE**

CFD computational fluid dynamics
DPM discrete phase model
RSM Reynolds stress model
PVC precessing vortex core
$L_g$ height of the second-stage cyclone inlet
$b$ width of the second-stage cyclone inlet
$L_g'$ height of the first-stage cyclone inlet
$b'$ width of the first-stage cyclone inlet
$D_s$ diameter of the exhaust pipe
$D_t$ diameter of the hopper
$D_w$ diameter of the two-stage cyclone
$D$ diameter of the second-stage cyclone
$C_1$ height of the second-stage cyclone inlet
$C_2$ width of the second-stage cyclone inlet
$St_{\text{max}}$ Stokes number of the maximum particle
$d_{\text{max}}$ particle maximum size
$p$ particle density
$V_{\text{in}}$ inlet gas velocity
$St_{\text{mean}}$ Stokes number of the cut size particle
$d_{\text{mean}}$ particle cut size
$D_{\text{in}}$ inlet equivalent diameter
$E_{\text{u}}$ Euler number
$\Delta P$ pressure drop
$\rho$ gas density
$D_{\text{ij}}$ diffusion term
$\phi_{\text{ij}}$ pressure strain term
$G_{\text{ij}}$ production term
$e_{\text{ij}}$ dissipation term
$S$ user-defined source term
$m_p$ particle mass
$\mu$ fluid phase velocity
$\mu_p$ particle velocity
$F$ additional force
$\tau_p$ particle relaxation time
$C_d$ drag coefficient
$Re$ relative Reynolds number

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