Effect of Inlet Air Volumetric Flow Rate on the Performance of a Two-Stage Cyclone Separator

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ABSTRACT: It is very important to improve the cyclone separator separation efficiency for fine particles. On the basis of the Reynolds stress model (RSM), a new two-stage cyclone separation device is modeled and the model is simulated under six kinds of air volumetric flow rate conditions. The two-stage cyclone separator was then tested in the laboratory and the experimental data were compared with the simulation data. The results show that the RSM model can predict the performance of the two-stage cyclone separation device with high accuracy. Increasing of the air volumetric flow rate can not only improve the separation efficiency of the two-stage cyclone separator, but also effectively change the classification range. Because of the centrifugal force, even if the pressure drop is low, the 1st-cyclone can completely separate particles above 5.0 μm. When the air volumetric flow rate is more than 290 m³/h, the 2nd-cyclone can effectively separate the particles below 2.0 μm. The study also confirmed the nonlinear relationship between the pressure drop and the cut-off particle size and the maximum particle size. When the pressure drop exceeds a certain value, there is no longer any effect on the cut-off particle size and the maximum particle size.

1. INTRODUCTION

Because of their convenient operation and relatively low operating costs, cyclones are widely used in the chemical industry, food engineering, and environmental engineering.1,2 The principle of a cyclone separator is to use different centrifugal forces of particles with different particle sizes to classify particles. However, the cyclone separator also has its disadvantages. For particles below 5 μm, the separation efficiency is often very low.3,4

As Morse’s first conical cyclone was introduced in 1886, scientists have conducted a variety of studies on cyclones to improve their performance. The main research methods of cyclones include: (1) experimental analysis; (2) theoretical empirical formula; (3) statistical analysis; and (4) numerical computation of computational fluid dynamics (CFD).5–7 Although each method can realize the design and optimization of cyclones, the numerical simulation method of CFD has more obvious advantages. It not only can quickly change parameters, but also can express air flow field and trajectory more intuitively, and has stronger visibility.

Separation efficiency and pressure drop are two important performance indicators of cyclone separators. The scientists used CFD to conduct a large number of numerical simulations on cyclone separators and compared them with experimental values.7–12 Many important conclusions have been obtained. Some scientists have used algorithms to optimize cyclone parameters to obtain the best parameters for the separator.13–15 Some scientists use electric and magnetic fields to improve the separation efficiency of cyclones.6,17 However, changing the cyclone separator structure is the most important way to optimize the performance of the cyclone separator.

Hosokawa Micron Group is one of the world’s leading suppliers of powder-processing equipment. It has the most extensive experience and cutting-edge powder-processing technology. However, the separation range of the two-wheel classifier with the smallest particle size is only 2–10 μm. There is no corresponding equipment for particle grading requirements below 2 μm.

In this work, a two-stage cyclone separator was designed, consisting of a 1st-cyclone and a 2nd-cyclone. This development is impressive because of its compact design. The 1st-cyclone has high separation efficiency for large particles and can effectively reduce 2nd-cyclone separation pressure. The 2nd-cyclone has high separation efficiency for small particles and can effectively separate small particles. Using a combination of experimental and numerical simulation methods, it was found that the cyclone separator not only completely separates particles larger than 5.0 μm, but also effectively separates particles below 2.0 μm.

2. NUMERICAL SIMULATION

2.1. Mathematical Model. The main methods for simulating the continuous phase of the cyclone separator are renormalized group (RNG k-ε), differential stress model, large
Reynolds-averaged Navier–Stokes (RANS) turbulence model that ANSYS Fluent provides. Abandoning the isotropic eddy-viscosity hypothesis, the RSM closes the Reynolds-averaged Navier–Stokes equations by solving transport equations for the Reynolds stresses, together with an equation for the dissipation rate. This means that five additional transport equations are required in two-dimensional flows, in comparison to seven additional transport equations solved in three-dimensional flows.\(^1\)

As the RSM accounts for the effects of streamline curvature, swirl, rotation, and rapid changes in strain rate in a more rigorous manner than one-equation and two-equation models, it has greater potential to give accurate predictions for complex flows. This article uses RSM for continuous phase simulation. The mathematical models are shown below.\(^1\)

\[
\frac{d\rho p}{dt} = F_d (u - u_p) + \frac{g_x (\rho_p - \rho)}{\rho_p} + F_s
\]

where \(u_p\) is the velocity of the particle; \(u\) stands for the velocity of the continuous phase; \(\rho_p\) denotes the density of the particle; \(\rho\) stands for the density of the continuous phase; \(g_x\) denotes the acceleration of gravity; \(F_d\) is the particle resistance; and \(F_s\) represents the other force.

### 2.2. Physical Model

The two-stage cyclone separator consists of a 1st-cyclone and a 2nd-cyclone. The 2nd-cyclone has two inlets and can reduce the low pressure drop without affecting the performance of the cyclone separation. The cyclone system base plate can be disassembled. It is convenient to clean after each experiment. The two-stage cyclone geometry model and its parameter dimensions are shown in Figure 1.

### 2.3. Boundary Condition Settings

In order to save computing resources and shorten the calculation time, the following hypotheses are made for the numerical simulation conditions: (1) the temperature field is constant; (2) the fluid is not compressible; and (3) the flow within the area is completely disordered. The parameters of the particles are completely set according to the experimental results. According to the actual conditions of the experimental device, the boundary conditions are set as shown in Table 1.

### 2.4. Grid Independence Study

The model was meshed using ANSYS Meshing 17.0. Four grids were used for the grid independence study. Element quality, skewness, orthogonal quality, and \(\gamma^*\) were used to evaluate the mesh quality, as shown in Table 2. The element quality option provides a composite quality metric that ranges between 0 and 1. A value of 1 indicates a perfect cube or square, whereas a value of 0 indicates that the element has a zero or negative volume. According to the definition of skewness, a value of 0 indicates an equilateral cell (best) and a value of 1 indicates a completely

### Table 1. Boundary Condition Types and Settings

| type         | property   | value         | type         | property   | value         |
|--------------|------------|---------------|--------------|------------|---------------|
| general      | solver type| pressure-based| model        | viscous    | RSM           |
|              | time       | steady        |              | discrete phase | on            |
| residuals    | convergence criteria | 10^{-5} | viscous Reynolds-stress model | linear pressure–strain |
| air          | density    | 1.225 kg/m\(^3\) | outlet      | velocity inlet | 12/17/25/32/41/47 m/s |
|              | viscosity  | 1.79 \times 10^{-5} Pa-s | inlet      | pressure inlet | 0 Pa          |
| inlet1       | boundary condition | interior | inlet2       | boundary condition | interior |
| particle     | min diameter | 0.1 μm | particle     | density     | 2800 kg/m\(^3\) |
|              | max diameter | 10.0 μm |              | inlet concentration | 1040 mg/m\(^3\) |
|              | mean diameter | 1.73 μm |              | spread parameter | 2.42          |
|              | injection type | surface |              | number of articles released | 49 000      |

\(^{1}\) The mathematical models are shown below.

\[
\frac{\partial}{\partial t}(\rho \pi_i \pi_j) + \frac{\partial}{\partial x_k}(\rho U_i \pi_i \pi_j) = D_{ij} + 
\phi_{ij} + G_{ij} - \varepsilon_{ij} + S
\]

Among them, \(i\), \(j\), and \(k\) are the three directions in the Cartesian coordinate system. \(D_{ij}\), \(\phi_{ij}\), \(G_{ij}\), \(\varepsilon_{ij}\), \(S\) are the proliferation term, the pressure–strain term, the production term, the dissipation term, respectively. \(u_0\), \(u_1\), and \(u_2\) represent the speed fluctuation.

The volume of particles in the cyclone is small, and its volume fraction is much less than 10%, so it can be considered that it does not affect the air flow. The discrete phase model (DPM) belongs to the Euler–Lagrange model. The continuous phase is described by the Euler method, and the discrete phase is described by the Lagrange method. Turbulence was emulated for particles by using the random walk model. The mathematical models are shown below.\(^2\)

\[
\frac{du_p}{dt} = F_d (u - u_p) + \frac{g_x (\rho_p - \rho)}{\rho_p} + F_s
\]
Rammler distribution and most of the particle sizes are below counter. The results are shown in Figure 2. As can be seen measured using an AeroTrak TSI 9306-V laser particle size distribution of the talcum powder was small and can be ignored because no particles were clogged in from Figure 2, the feed particles conform to the Rosin-Rammler distribution function is shown below.19

\[ y = \frac{k}{\lambda} \left(\frac{x}{\lambda}\right)^{1-1} e^{-(x/\lambda)^{1-1}} \]  

(3)

where \( k \) represents the shape parameter; \( f \) represents the proportional parameter.

The talcum particle size distribution data were imported into Origin and data fitting was performed. The formula for the particle size distribution is as follows: \( R^2 \) is 0.98.

\[ y = 1.4 \left(\frac{x}{1.73}\right)^{1.42} e^{-(x/1.73)^{1.42}} \]  

(4)

The shape parameter of the inlet particle size distribution is 2.42, and the proportional parameter is 1.73. That is, the inlet particle spread parameter is 2.42, and the median diameter (also called cut-off diameter) is 1.73 \( \mu m \).

3. EXPERIMENTAL MATERIALS AND METHODS

3.1. Materials. Talcum powder is common and can be controlled within 20 \( \mu m \) as needed. Therefore, talcum powder with a density of 2800 kg/m\(^3\) was selected as the feed particles. Although the particle dispersion state may be slightly different under different air volumetric flow rates, these differences are small and can be ignored because no particles were clogged in the dispersing device even under a low air volumetric flow rate. The particle size distribution of the talcum powder was measured using an AeroTrak TSI 9306-V laser particle counter. The results are shown in Figure 2. As can be seen from Figure 2, the feed particles conform to the Rosin-Rammler distribution and most of the particle sizes are below 10 \( \mu m \).

The Rosin-Rammler distribution function is shown below.19

The particle concentration on the outlet of the two-stage cyclone was measured by CEL-712 Microdust Pro. The instrument is produced by the American company Casella with an accuracy of 0.001 mg/m\(^3\). The pressure drop is measured by an inclined differential pressure gauge.

4. EXPERIMENTAL VERIFICATION

4.1. Pressure Drop. Pressure drop is one of the important indexes of the performance of cyclone separators. It is mainly caused by the friction between the fluid and the wall and the internal vortex flow.\(^7\) As the mass loading of particles will affect the pressure drop, all pressure drops are measured with particle loading. The 2nd-cyclone has two inlets. The experiment found that the two inlet pressures are basically equal. However, for the accuracy of the experiment, the actual 2nd-cyclone inlet pressure is the average of the two inlet pressures of the 2nd-cyclone. The obtained 1st-cyclone pressure drop, 2nd-cyclone pressure drop, and total pressure drop were compared with the simulation results. The result is shown in Figure 4.

From Figure 4, it is observed that the 1st-cyclone pressure drop, the 2nd-cyclone pressure drop, and the total pressure drop increased with the increase of air volumetric flow rate, which is consistent with the results of other scholars.\(^22\)\(^-\)\(^25\) The 1st-cyclone has only a cylindrical portion and does not have a

![Figure 2. Talcum powder particle size distribution.](image-url)
cone portion. This results in a smaller 1st-cyclone vortex and lower pressure drop. When the air volumetric flow rate is 332 m$^3$/h, the pressure drop is only one-tenth of the 2nd-cyclone. The 2nd-cyclone volume is small, and the inlet air speed is much larger than that of the 2nd-cyclone. This leads to more intense internal eddy currents and more energy loss. Therefore, the 2nd-cyclone pressure drop is the main component of the total pressure drop.\textsuperscript{15} There is a certain error between the experimental value and the simulation result. It is mainly due to the presence of swirling flow at the 2nd-cyclone inlet, which makes it difficult to measure the pressure. In order to obtain the pressure at the 2nd-cyclone inlet, no less than 10 measurements were taken and averaged as a result. Error bars represent standard errors.

In general, the experimental value of pressure drop is greater than the simulation value. However, the experimental results of pressure drop under different air volumetric flow rate conditions are consistent with the overall trend of the simulation results, and the relative errors are all within 5\%, indicating that the simulation results are reliable.

4.2. Separation Efficiency. Figure 5 shows the relationship between separation efficiency and air volumetric flow rate in a two-stage cyclone separator (the error bars represent standard errors). It can be seen that the simulated and measured values of 1st-cyclone separation have been increasing with the increase of air volumetric flow rate. The main reason is that there is no cone section in the 1st-cyclone, and it is mainly separated by the cylinder section. Even at the maximum air volumetric flow rate condition, the inlet air speed does not reach the 1st-cyclone critical air speed.

The simulated and measured values of the 2nd-cyclone efficiency and total efficiency increase first with the increase of air volumetric flow rate, and then tend to be stable. At the time of stabilizing, the air volumetric flow rate was 226 m$^3$/h, and the 2nd-cyclone inlet air speed was 20.37 m/s. This air speed is called the maximum efficiency inlet speed.\textsuperscript{23,26} As the 2nd-
Particulate concentration is significant in cyclone separation. The collection efficiency is decreased because of the large centrifugal force, and particles cannot reach the cyclone and another part rises inside the first cyclone. However, in the first cyclone inlet, some particles are deposited at the bottom of the first cyclone. After entering the first cyclone, some particles were sampled on the bottom of the second cyclone under the effect of gravity. It can be seen that the particles below 5.0 μm range rotate directly into the second cyclone at the top of the first cyclone. It does not undergo the process of falling and then rising within the first cyclone. A spiral particle deposition zone is formed on the inner wall of the first cyclone cylinder. It clearly shows the phenomenon of particle clustering similar to the results observed in the literature and the simulation results.

When the air volumetric flow rate is 226 m$^3$/h, the particle deposition on the inner wall of the first cyclone cylinder is shown in Figure 8a, and the particle deposition on the two-stage cyclone base plate is shown in Figure 8b. Although talcum powder is lubricious and extremely unstable, a spiral particle deposition zone is formed on the inner wall of the first cyclone cylinder. It strongly shows the phenomenon of particle clustering during particle separation similar to the results observed in the literature and the simulation results. The particle deposition area formed around the two-stage cyclone base plate and the particle deposition area formed by the bottom plate center hopper are also similar to the simulation results.

5. RESULTS AND DISCUSSION

5.1. Particle Trajectory of Different Particle Sizes. Figure 6 shows several typical particle transport trajectories of different particle sizes at an air volumetric flow rate of 226 m$^3$/h. It can be seen that the particles below 5.0 μm are mostly rotated from the inlet to the bottom along the inner surface of the first cyclone. Then, it is rotated from the bottom to the second cyclone. After entering the second cyclone, some particles were deposited on the bottom of the second cyclone under the effect of centrifugal force, and some particles were discharged from the outlet. We can also find an interesting phenomenon. Part of the particles in the 0.5−1.0 μm range rotate directly into the second cyclone at the top of the first cyclone. It does not undergo the process of falling and then rising within the first cyclone. Particles above 5.0 μm have a large centrifugal force because of their large diameter. After entering the first cyclone from the inlet, some particles are deposited at the bottom of the first cyclone and another part rises inside the first cyclone. However, because of the large centrifugal force, the particles cannot reach the second cyclone inlets. The collection efficiency of large particles is significantly improved.

5.2. Body Concentration Distribution with Different Air Volumetric Flow Rates. Figure 7 shows the distribution of the two-stage cyclone concentration under different air volumetric flow rate conditions. It can be seen that as the air volumetric flow rate increases, the air speed at the first-cyclone inlet increases. The concentration of spiral particles and the concentration of sediment particles on the outer ring of the floor gradually increases. It shows that the first-cyclone separation efficiency increases gradually, which is consistent with the experimental results. However, the particle concentration of the second-cyclone hopper does not gradually increase when the air volumetric flow rate increases. When the air volumetric flow rate increased from 85 to 177 m$^3$/h, the particle concentration of the second-cyclone hopper increased with the increase of air volumetric flow rate. When the air volumetric flow rate increased from 177 to 332 m$^3$/h, the particle concentration of the second-cyclone hopper first decreased and then increased. The reason for this is that as the air volumetric flow rate increases, the efficiency of the first-cyclone separation increases, and the number of particles entering the second-cyclone decreases. Even if the second-cyclone separation efficiency increases with the increase of the air volumetric flow rate, because of the decrease of the particle amount, the concentration of the second-cyclone hopper particle decreases.

When the air volumetric flow rate is 226 m$^3$/h, the particle deposition on the inner wall of the first-cyclone cylinder is shown in Figure 8a, and the particle deposition on the two-stage cyclone base plate is shown in Figure 8b. Although talcum powder is lubricious and extremely unstable, a spiral particle deposition zone is formed on the inner wall of the first-cyclone cylinder. It strongly shows the phenomenon of particle clustering during particle separation similar to the results observed in the literature and the simulation results. The particle deposition area formed around the two-stage cyclone base plate and the particle deposition area formed by the bottom plate center hopper are also similar to the simulation results.
under different air volumetric flow rate conditions. It can be seen from the figure that when the inlet air volumetric flow rate is small, the efficiency of the 1st-cyclone and 2nd-cyclone is very low for particles smaller than 2.0 μm. With the increase of air volumetric flow rate, the efficiency of 1st-cyclone separation did not change significantly for particles below 2.0 μm, and it was basically stable at about 60%. For particles below 2.0 μm, the 2nd-cyclone separation efficiency is significantly increased. When the air volumetric flow rate is more than 290 m³/h, the 2nd-cyclone separation efficiency is basically above 90% for particles below 2.0 μm. That is to say, when the air volumetric flow rate is more than 290 m³/h, the two-stage cyclone separator can effectively separate particles with 2.0 μm or less.

By contrast, a strange phenomenon can be found. The 2nd-cyclone has a low particle separation efficiency of about 1.0 μm, and some even have a lower separation efficiency than 0.3 μm particles. This strange phenomenon is known as "fish-hook" phenomenon. As the inlet air volumetric flow rate increases, the "fish-hook" is no longer so prominent, consistent with the results of the Kilavuz and Gülsoy studies. The reason for this may be related to the particle migration trajectory mentioned earlier, and further research is needed.

Particles in the 0.5–1.0 μm range are directly dragged to the vortex finder, resulting in reduced efficiency. When the air

Figure 8. Experimental particle deposition: (a) the inner wall of the 1st-cyclone cylinder; (b) base plate.

Figure 9. Effect of air volumetric flow rate on classification efficiency: (a) Q = 85; (b) Q = 120; (c) Q = 177; (d) Q = 226; (e) Q = 290; (f) Q = 332.
volumetric flow rate is greater than 120 m³/h, the 2nd-cyclone separation efficiency is above 70% for all particle sizes.

5.4. Influence of Pressure Drop on Cut-Off Diameter and Maximum Diameter. The cut-off size is defined as the diameter at which 50% of the particles are separated and the maximum size is defined as the diameter of the largest particle that is captured. Figure 10 shows the relationship between the cut-off size, the maximum particle size, and the total pressure drop. It can be seen that even with a minimum pressure drop of 650 Pa, the maximum size of the 2nd-cyclone is 2.03 μm. However, because of the low efficiency of 2nd-cyclone separation for particles below 2.0 μm at this time, it cannot completely satisfy the grading requirements for particles below 2.0 μm.

As expected, the 1st-cyclone and 2nd-cyclone cut-off particle size and maximum particle size decrease with the increase of pressure drop. The cut-off diameter is mainly related to the cyclone circulation in the body. The larger the swirling flow, the greater the centrifugal force on the particles. Correspondingly, the dust removal efficiency becomes higher and the cut-off particle size becomes smaller. The conclusions of the study are consistent with those of Liu.34 As mentioned above, when the air volumetric flow rate is greater than 290 m³/h, the 2nd-cyclone particle separation efficiency below 2.0 μm is more than 90%, and the pressure drop at this time is 8182 Pa. When the pressure drop is less than 8182 Pa, the 1st-cyclone and 2nd-cyclone cut-off particle size and maximum particle size decrease with the increase of pressure drop. Then, with continued increase in the pressure drop, the cut-off particle size and maximum particle size of the 2nd-cyclone basically no longer change.

6. CONCLUSIONS

This paper mainly studies the effect of air volumetric flow rate on the performance of two-stage cyclone separation. Comparing the experimental value with the simulated value, the pressure drop error is within 5%, and the efficiency error is within 10%. It shows that the simulation results can well predict the performance of two-stage cyclone separation.

For the two-stage cyclone separator, the 1st-cyclone can increase the collection efficiency of the large particles, and the 2nd-cyclone can increase the collection efficiency of the small particles. When the air volumetric flow rate is greater than 177 m³/h, the collection efficiency of all particle sizes is greater than 75%. When the air volumetric flow rate is more than 290 m³/h, the 2nd-cyclone separation efficiency is basically above 90% for particles below 2.0 μm.

Further, on observing the relationship between the pressure drop and the cut-off diameter and the maximum diameter, it is found that the cut-off diameter and the maximum diameter are affected when the pressure drop is within a certain range. With the increase of air volumetric flow rate, the 1st-cyclone cut-off diameter ranges from 1.53 to 1.26 μm, the maximum diameter range from 7.11 to 3.21 μm, the 2nd-cyclone cut-off diameter from 1.00 to 0.63 μm, and the maximum diameter range from 2.03 to 1.07 μm.

The inadequacy of this study is that the pressure drop is high and the cut-off particle size is limited to 0.63 μm. With continued increase in the pressure drop, the cut-off particle size cannot continue to decrease. The next step is to adjust the inlet size and the air speed ratio so as to reduce the pressure drop, increase the separation efficiency, and reduce the cut-off diameter.

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Notes

The authors declare no competing financial interest.

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