Study on Particle-Size Control of Hydrocyclone for Slurry Recycles

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Abstract: Particle size control is very important in the shield slurry separation. The structural parameters and separation efficiency of desilter separation efficiency were studied using numerical simulations. In this study, slurry treatment process was designed firstly, and then the influence including the diameter of the overflow port, the size of the cone, the length of cylinder and the diameter of the bottom flow on the separation efficiency were studied. In the hydrocyclone, the minimum tangential velocity occurs at the center of the cyclone, which makes it possible to separate materials more efficiently. The pressure distribution is consistent with the pressure characteristics of combined vortex motion. After obtaining the optimal design, the separation ability of the hydrocyclone was greatly improved. The 75 μm and 100 μm particles recycle efficiency increase 8% and 11% respectively. The results of this study provide a numerical basis for the optimization of hydrocyclone system.

1. Introduction

Slurry shield machines are used in subways, municipal engineering, and other underground tunnels in the construction of a wide range of applications. Shield slurry treatment equipment reveals that hydrocyclones are the most widely used desanding equipment [1]–[3]. The basic structure of a hydrocyclone, which is used for the separation of solid–liquid mixtures, includes an overflow port, underflow port, and feed port. Its basic principle is density–drag mechanical separation: the mixture is injected into the flow cavity where it forms a vortex on the interior surface; as the flow travels downwards, the chamber constricts, and an upward-travelling inner vortex forms [4]. The centrifugal inertia of particles drives them to the outer vortex, which exits through the underflow port. However, the centrifugal inertia will fail to keep the particles in the outer vortex if the drag experienced by the particles is sufficiently large; in this case, they will enter the inner vortex and exit through the overflow port [5],[6]. The main function of the cyclone is to remove mud particles with a particle size greater than 75 μm in the mud and retain particles with a particle size less than 75 μm.

Both theoretical and numerical methods have been adopted to study the theory of cyclones; however, owing to the complex flow field within a cyclone, theoretical research alone is not sufficient. With the common use of computational fluid dynamics (CFD), current theoretical research on hydrocyclones is mainly performed using numerical simulations. Boysan et al. [7] used the standard k-ε turbulence model to numerically simulate the internal flow field of a hydrocyclone; however, because k-ε is not suitable for the simulation of strongly swirling flow, the conclusion was that a strong vortex will
produce additional viscosity. Cullivan et al. [8], Schuetz et al. [9], and Wang et al. [10] used Reynolds stress models in subsequent studies to simulate the flow field of a hydrocyclone with high accuracy. Delgadillo and Rajamani [11], Wang et al. [12], and Vakamalla and Mangadoddy [13] conducted in-depth studies on the separation and flow patterns of hydrocyclones based on the RSM and LES models. Using CFD, Banerjee et al. [14] developed a new complex mechanical dynamics model based on vortex flow in a limited environment for water splitting in hydrocyclones. Some researchers have studied the separation performance of hydrocyclones, taking into account factors such as the size of the cyclone, the diameter of the spigot, the inlet flow rate, curvature radius, and the inlet solid concentration [15]–[18]. Hwang and Dubey et al. studied the vortex finder with extra conical shapes and diameters of hydrocyclones through experiments and numerical simulations [19], [20]. This group used FLUENT to simulate the three-dimensional flow field of centrifuge and the dewatering efficiency of sludge pretreatment.

In China, most shield slurry separation processes are based on past experience or direct use of foreign processing equipment—i.e., there is no domestic targeted research. In this paper, we mainly studied particle size control using hydrocyclones in the shield slurry control process via simulations. By studying the velocity field and the pressure field distribution of the cyclone, the single-factor structural parameters of the hydrocyclone are optimized. And the separation performance under different inlet flow was studied. These provide guidance for ensuring the quality of the treated shield slurry.

2. Methods

2.1. The Process Flow
The larger diameter soil particles are first removed from the slurry by sieving, and the slurry enters the desander hydrocyclone after preliminary precipitation. The overflow from the desander, which contains the smaller solid particles, is piped to the desilter (Fig. 1) for secondary swirling, and a horizontal screw centrifuge concentrates the underflow of the desander and desilter into a solid phase. The water produced during the concentration process re-enters the sedimentation tank. The overflow sludge from the slime treatment, which contains fine particles, enters the regulating pot, thereby realizing the reuse of the slurry. In the final stage of the shield slurry treatment, the pretreated slurry is graded using a two-phase cyclone. The treated underflow stream is used as waste slurry, and the overflow is used as shield slurry for reuse. The shield slurry separation system is shown in Fig. 1.

![Figure 1. The desilter](image)

The cyclone separation performance at this stage is the key factor to the quality of the slurry in the process; improper handling will cause the slurry to deteriorate. If the hydrocyclone separation efficiency is too low, large soil particles will be re-mixed into the cycle, resulting in a slurry density that is too large. Specifically, soil particles less than 75 μm will be lost from the slurry. In this study, we are particularly concerned with the separation of this grade of the particles because 75-μm particles ensure the operation of the shield.

2.2. Model and Mesh
The overall height of the hydrocyclone is 440 mm. The basic dimensions of the cyclone used for simulation are shown in Table 1. The rectangular inlet is tangent to the cylindrical circle with a length of 80 mm. Hexahedral meshing is applied to the model, and the entire calculation domain is divided into 13 sub-regions via horizontal and vertical cutting. Firstly, the Gambit pave and map commands are used to develop the grid at the interface of the inlet and the cylinder, and then they are used to mesh the entire cyclone cylinder. The meshes are all hexahedral meshes with uniform grid size. In this study, the velocity distribution of an interface was selected, and the distribution values did not change under different density grids. This proves that grid independence is true. After grid-independence verification, the segment was divided into 392166 individual cells.

### Table 1. Basic dimensions cyclone

| Project               | Size     |
|-----------------------|----------|
| Main diameter of the cyclone (mm) | 100      |
| Overflow pipe         |          |
| Diameter (mm)         | 30       |
| Insertion depth(mm)   | 50       |
| Inlet (mm × mm)       | 16m×30mm |
| Cylinder length (mm)  | 120      |
| Underflow             |          |
| Diameter (mm)         | 15       |
| Length(mm)            | 20       |
| Angle of cone(°)      | 20       |

3. Simulation Results and Analysis
The solid particle size is 75 μm, the mass fraction of the solid phase is 20%, and the inlet speed is 6m/s. The dynamic viscosity of the two-phase flow is 7 MPa·s. FLUENT was used for numerical simulation. The simulation results of the velocity distribution, pressure distribution, and separation performance are presented below.

3.1. Velocity Distribution
Fig. 2 illustrates the two-phase flow through the inlet and into the cyclone inside the hydrocyclone. The fluid inside the hydrocyclone forms two swirling flows in opposite directions of motion from the wall to the center: the fluid at the center flows upwardly and exits through the overflow port, whereas the fluid near the wall of the cyclone flows downwardly and exits through the underflow port. The overflow and underflow continue rotating, where the internal cyclone fluid swirl effect is better, which is consistent with the expected results.

![Figure 2. Flow path of the vortex chamber](image)
The tangential velocity distribution curves of the flow within the cylinder were obtained at Fig. 3(a). Because of the no-slip conditions at the wall, the velocities at the walls of the hydrocyclone (radial position of 50 mm) and overflow tube (radial position of 15 mm at \(Z = 40\) mm and \(Z = 50\) mm) are zero. It can be seen that a cyclone column has formed within a stable tangential swirl—the flow state is consistent with combined vortex flow. The flow field in the cylinder is symmetrical, and the minimum tangential velocity occurs at the center of the cyclone, which is conducive to the generation of centrifugal inertia, which makes it possible to separate materials more efficiently. In the \(Z = 120\) mm section, owing to the interface between the cylinder and the cone, the tangential velocity fluctuates. It can be seen from the simulation that the swirl distribution is generally consistent in different sections of the cylinder: the swirl is divided into two swirls—inner and outer—but the rotation direction is consistent. However, the outer swirl is significantly stronger than the internal swirl. The maximum-magnitude tangential velocity appears near the overflow port radius, forming a quasi-forced vortex zone.

![Tangential velocity distribution](image)

**Figure 3.** Tangential velocity distribution in the hydrocyclone: (a) cylinder region, (b) cone region.

Next, we consider the flow at five axial positions within the cone, namely, 140 mm, 200 mm, 260 mm, 300 mm, and 360 mm. Fig. 3(b) shows that the fluid within the cone generally consists of the higher swirl state, as the tangential flow velocity at different positions is generally consistent. This shows that the cone maintains the velocity of the swirl and accelerates the overall flow. However, the swirl is asymmetric, and the position of the maximum-magnitude tangential velocity varies in different sections. This position gradually shifts to the middle as cone constricts. This occurs because the inner vortex of the cylinder becomes less influential on the flow field of the cone. Within the \(Z = 360\) mm section, the flow is travelling through the outlet, so the tangential velocity near the central position rapidly vanishes.

### 3.2. Pressure Distribution
Because the liquid enters the hydrocyclone at a fixed speed and develops a tangentially graded pressure distribution, the liquid in the cavity completes the flow state transition. The pressure distribution is consistent with the pressure characteristics of combined vortex motion, as shown in Fig. 4. The static pressure distribution shows that the static pressure in the cylindrical part of the hydrocyclone is minimized along the radial distance at the center of the hydrocyclone. This occurs because the vortices dissipate energy as they accelerate the flow through the overflow and underflow ports. Throughout the hydrocyclone, the static pressure isobars are approximately parallel to the cylinder wall, and the pressure decreases toward the center of the cyclone.

### 3.3. Distribution of Solid Phase
When the inlet velocity is 6 m/s, mud particle diameter is 75 μm, slurry phase is 20%, simulated distribution of solid phase. Slurry enters the internal hydrocyclone with high-speed by centrifugal force, high density particles gradually deposited on the outer wall, and then continue to downwards flow out via the underflow. Water mainly gathered in the center to exclude from the overflow port. The two-phase separation is realized in the swirl cylinder, and the separation effect is more obvious in
the cone section. It can also be seen that the oscillation of the spiral flow at the center of the cone is obvious in different sections (Fig. 5).

![Figure 4](image)

**Figure 4.** Static pressure distribution ($X = 0$ mm)

![Figure 5](image)

**Figure 5.** Distribution of solid phase in different position of cyclone

### 3.4. Influence of Structural Parameters on the Separation Performance

Four diameters of soil particles $30 \mu m$, $50 \mu m$, $75 \mu m$ and $100 \mu m$ were selected to study the separation efficiency.

#### 3.4.1. Overflow pipe diameter

Four hydrocyclones, with overflow pipe diameters of $26$ mm, $30$ mm, $34$ mm, and $38$ mm, were numerically simulated to evaluate the separation performance. The distribution of soil particles when the diameter of the overflow pipe is $30$ mm. As the particle size of
the soil becomes larger, the concentration of particles leaving through the overflow port decreases, thereby increases the separation efficiency, which is in accordance with the demands of the hydrocyclone. The post-processing functions available in FLUENT provide direct access to the overflow and underflow two-phase and mixed-phase mass flow rates and the cyclone pressure drop. The separation efficiency and pressure drop data are shown in Table 2. For an overflow port diameter of 38 mm, separation efficiency of the larger particles decreases significantly. The results also show that the pressure drop decreases as the overflow pipe diameter increases, so there is less energy dissipation inside the cyclone. When the diameter of the overflow pipe is 34 mm, the differences between the separation efficiencies of particles of different diameters are largest. Thus, the best overflow pipe diameter is 34 mm.

| Table 2. Separation efficiency and pressure drop under different overflow pipe diameters. |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Overflow pipe diameter [mm]     | Solid particle diameter [μm] | Separation efficiency [%] | Pressure drop [Pa] | Overflow pipe diameter [mm] | Solid particle diameter [μm] | Separation efficiency [%] | Pressure drop [Pa] |
| 26                              | 30               | 32              | 46653           | 34              | 30               | 23              | 33365           |
|                                 | 50               | 42              | 43256           | 50              | 75               | 64              | 32486           |
|                                 | 75               | 67              | 44738           | 100             | 100             | 81              | 32663           |
|                                 | 100              | 82              | 48652           | 30              | 30              | 21              | 34102           |
|                                 | 30               | 27              | 38566           | 34              | 30              | 21              | 30306           |
| 30                              | 50               | 40              | 39628           | 38              | 50              | 36              | 29558           |
|                                 | 75               | 66              | 38128           | 100             | 75              | 64              | 29036           |
|                                 | 100              | 81              | 37521           |                 |                 |                 |                 |

3.4.2. **Cone taper angle.** Selecting an overflow pipe diameter of 34 mm, five hydrocyclones, with taper angles of 14°, 16°, 18°, 20°, and 22°, are numerically simulated to evaluate the separation performance. When the cone angle is reduced to 14°, the small particles are excessively removed, and the separation efficiency of 100 μm particles is greatly reduced. When the taper angle is 18°, the separation efficiency of 30-μm particles is 24%, and the separation efficiency of 100 μm particles is 92%. Based on the pressure drop and separation efficiency, the optimal cone angle is 18°.

3.4.3. **Underflow pipe diameter.** Selecting an overflow pipe diameter of 34 mm and a taper angle of 18°, four underflow pipe diameters of 12 mm, 15 mm, 18 mm, and 21 mm are numerically simulated. When the underflow diameter is 21 mm, the separation efficiency for 30-μm particles exceeds 30%, whereas the separation efficiency of 100 μm particles reaches 94%. This wastes soil particles beneficial to the pulp. When the underflow pipe diameter is 18 mm, the split ratio of the underflow is only 25%. The underflow diameter has little effect on the pressure drop of the cyclone, so the under flow diameter remains unchanged at 15 mm.

3.4.4. **Cylinder height.** Based on the above optimized parameters, the four cylinder lengths of 80 mm, 100 mm, 120 mm, and 140 mm are numerically simulated. The results of the simulations show that the length of the cylinder has little effect on the pressure drop of the cyclone, so the length of the cylinder remains unchanged at 100 mm.

4. **Conclusion**
In this paper, the influence of the internal flow field and hydrocyclone structure on the separation performance of the core device in a slurry separation system was studied using numerical simulations. The hydrocyclone separation performance experiment, simulation results, and experimental conclusions are summarized below:

(1) The flow field in the cylinder is symmetrical, and the minimum tangential velocity occurs at the center of the cyclone, which is conducive to the generation of centrifugal inertia, which makes it possible to separate materials more efficiently.

(2) The overflow pipe diameter of the hydrocyclone has a strong influence on the small particle separation efficiency in the mixed solution. A larger overflow pipe diameter facilitates recovery of small particles. The underflow diameter and cylinder length of the cyclone have negligible influence on the separation efficiency and pressure drop of the cyclone, much less than that of the overflow pipe and the cone angle.

(3) The inlet flow rate has a strong influence on the separation performance of the cyclone. Initially, increasing the flow rate improves the separation efficiency, but too much flow reduces in the slurry residence time, resulting in decreased separation efficiency. From the simulation analysis, the separation efficiency was highest (72.6%) at an inlet speed of 12 m/s.

5. References
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