Solid/liquid separation performance of hydrocyclones with different cone combinations

Qiang Yang, Hua-lin Wang*, Yi Liu, Zhi-ming Li

State-Key Laboratory of Chemical Engineering, East China University of Science and Technology, Shanghai 200237, PR China

ABSTRACT

Hydrocyclones used for solid–liquid separation are usually composed of a single cone. In this paper, we designed hydrocyclones with two cone combinations for solid–liquid separation and studied the flow field and separation performance. Simulation and experimental results showed that when the second cone remained unchanged, the angle change of the first cone had significant effect on the value of three-dimensional velocities, flow split, separation efficiency, energy consumption, and separation sharpness, but little effect on the distribution of pressure and that of three dimensional velocities, the capacity and cut size. The bigger of the first cone’s angle, the smaller of the flow split and the higher the separation efficiency, the stronger of the centrifugal force, and the more the small particles in underflow. The smaller the angle change between the two cones, the larger the sharpness of the grade efficiency curve, i.e., the hydrocyclone is more suitable for the classification process.

1. Introduction

Hydrocyclones are widely used for particle separation, classification and thickening in many solid–liquid processes for their advantages such as simple structures, robust separation devices with no moving parts, small physical size of unit, and low installation and maintenance costs. In the recent years, the hydrocyclones have been widely applied in mineral processing [1], food [2], petrochemical [3], electro-chemical [4], textile and pulp [5], environmental [6], biological [7] and other industries.

The investigations on the design and performance of hydrocyclones have been continued for several decades. It is well known that the structure of the hydrocyclone and the operating parameters affect the hydrocyclone separation performance. For the established solid–liquid separation system, the structure of hydrocyclone is the determinant factor. To get satisfactory separation performance, a great number of investigations have been made concerning on the structure and the geometric dimension scale of hydrocyclones [8]. Some efforts have been made to improve certain performance indices of conventional hydrocyclones by introducing special structural modifications. For example, a solid core was inserted into the hydrocyclone to improve separation efficiency and reduce energy loss by stabilizing the tangential flow and canceling the air core [9], a diffuser type of vortex finder was introduced to reduce the energy loss by recovering the velocity head [10], a hydrocyclone with small diameter was used for separate small particles [11], and a hydrocyclone with spiral inner surface was developed to improve the separation sharpness by interrupting the boundary layer flow [12], etc. Also, some brand new structural hydrocyclones have been studied recently. For example, some new structures like new types of inlet, vortex finder, cone parts, underflow pipes, central insertions were designed to improve the separation efficiency, separation sharpness, cut size, capacity, flow split and energy loss efficiency of the hydrocyclone [13–16]. Chu et al. studied the effect of structural modification on hydrocyclone performance more comprehensively [17]. However, up to now, few experimental and simulation results have been obtained on the effect of hydrocyclone cone combinations on the solid–liquid separation performance and the flow field inside hydrocyclone yet. In this study, hydrocyclones with two cone combinations will be designed for solid–liquid separation, and the Computational Fluid Dynamics (CFD) method was used to simulate the flow fields inside hydrocyclones with different cone combinations, also the effect of hydrocyclone cone combinations on the separation performance will be experimentally studied.

2. Simulation parts

Three hydrocyclones with diameter of 100mm were designed in this study. The hydrocyclone geometry is shown in Fig. 1. They have the same type of inlet, outlet...
The multiphase flow in a hydrocyclone is quite complicated. In this work, pressure and velocity fields of the hydrocyclones with different cone combinations were numerically simulated using FLUENT computational fluid dynamics (CFD) software. Some works of simulation of hydrocyclones using the Reynolds stress model (RSM) have been reported to be suitable for modeling the flow in the hydrocyclone in recent years [18–20]. Therefore, the Reynolds stress model (RSM) of the hydrocyclone internal turbulent flow simulation is used in this paper. Gambit, which is the main preprocessor of Fluent, is used to create geometry, meshing and specifying boundary types of hydrocyclone. The created geometry and meshing are shown in Figs. 2 and 3. Boundary types are considered as inlet mass flow rate, overflow and underflow outlet pressure. The solid weight concentration of feed slurry was 4 wt%. Solid particles with different sizes varying between 1 and 60 μm were injected from the feed inlet boundary zone along the surface. Using Fluent the created geometry by Gambit can be read and simulation is done.

3. Experimental parts

3.1. Hydrocyclones

Three hydrocyclones are designed as that shown in Fig. 1.

3.2. Materials and methods

The feed was a mixture of solids and water. The solid was from the flue gas desulphurization (FGD) system of a power plant. The suspended solids were composed of CaSO₄·2H₂O with a purity of 90.15%, CaCO₃ with a purity of 2.55%, and fly ash with a purity of 1.17%. The density of solids was 2.39 g/cm³ (at 20°C) and the mean size of particle was 23.954 μm. The particle size distribution is illustrated in Fig. 4, which was measured by a laser granulometer (Master 2000).

![Fig. 1. Structure diagram of designed hydrocyclone in the work.](http://www.paper.edu.cn)
The schematic diagram of the experimental apparatus is illustrated in Fig. 5. The feed was pumped directly from the stirring tank to the hydrocyclones. The overflow and underflow samples that have been separated by the hydrocyclones were taken from the relevant pipelines. The flow meter and pressure gauge recorded the flow rate and the pressure of the inlet and overflow of each hydrocyclone. The experimental equipment is illustrated in Fig. 6.

Because the objective of this study is to understand the effects of different cone combinations on the hydrocyclone performance, the characteristics of feed slurry and the operating parameters were the same for each hydrocyclone in the experiments. The solid weight concentration of feed slurry was same with simulation in all the experiments. The inlet pressure of the hydrocyclone was changed from 0.06 MPa to 0.22 MPa. The underflow and overflow pressures were zero. The flow rates of the feed slurry and overflow of hydrocyclone were measured simultaneously. Samples were simultaneously taken from both the feed and underflow, and then the solid weight concentrations and the particle size distributions of the samples were measured.
4. Results and discussion

4.1. Distribution of pressure profiles

Pressure profiles had been simulated using FLUENT computational fluid dynamics (CFD) software. The axis and the wall pressure profiles of hydrocyclones are shown in Fig. 7. According to the axial pressure profile, it can be found that the pressure in the cylindrical section is the highest, followed by that in the first cone section and that in the second cone section near the underflow outlet, while the lowest one is the pressure in the overflow section. The isobars are “V”-like type, descending from the wall to the axis. According to the wall pressure profile, the isobars go down spirally rather than be perpendicular to the z-axis of hydrocyclones, which shows that the pressure in the equal-height areas axisymmetric to the central axis in the single-inlet hydrocyclone is not the same. The comparison of the axial and wall surface pressure profiles of hydrocyclones shows the cone combination has no significant influence on the distribution of pressure, but really has effect on the value of pressure drop in hydrocyclones. The pressure drop in hydrocyclone A is...
significantly higher than that in hydrocyclones B and C, and that in hydrocyclone B is slightly higher than that of hydrocyclone C. The results show that the bigger the angle of the first cone is, the higher the pressure drop will be.

The axis center pressure profiles of hydrocyclones are shown in Fig. 8. According to the axis center pressure profiles, the pressure of the axis center near the underflow is the highest, and declines from the underflow to the overflow area before the minimum pressure occurring in the cross-section of the vortex finder and the cylindrical section, and then increases gradually. The variation of the pressure is found mainly in the cone section, and increases with the cone angle. The negative pressure occurs in the cross-section of the vortex finder and the cylindrical section in hydrocyclone A.

4.2. Distribution of three-dimensional velocities

The position of vortex finder tip is defined as $Z = 0$. The four-dimensional velocity distributions in the position $Z = -50$, $-150$, $-250$ and $-400$ of the hydrocyclones are studied separately. The simulation results are described as follows.

4.2.1. Axial velocity

The axial velocity profiles in different cross-sections are shown in Fig. 9. The axial velocity in each cross-section basically shows a symmetric distribution, changing gradually from negative to positive in the direction from the wall to the centre. It can be seen that the fluid along the wall moves to the underflow outlet, and the downward velocity increases with its radial distance from the hydrocyclone axis. The fluid around the axis moves to the underflow outlet, and the upward velocity increases with its radial distance from the hydrocyclone wall. For hydrocyclone A, because of the great variation of cone angle, the axial velocity in the same cross-section also changes greatly. In the first cone, the maximum downward velocity in radial section of hydrocyclone A is higher than that in radial section of hydrocyclones B and C, while there is little difference among the maximum upward velocity in the axis of three hydrocyclones, as shown in Fig. 10. In conclusion, cone angle has a certain influence on the particle velocity down the wall. The particle velocity down the wall of the hydrocyclone with a small cone angle is higher than that of the hydrocyclone with a larger cone angle, but the combination of cone angle has no significant influence on the upward velocity of the particles in the central axis.

4.2.2. Radial velocity

The radial velocity profiles in different cross-sections are shown in Fig. 11. The radial velocity in the cross-section along the $Z$-axis is not symmetrically distributed around the axis due to the influence of single inlet. It increases gradually from wall to axis and
decreases sharply in the proximity of central axis. The variation of cone angle has large influence on the radial velocity. The absolute value of radial velocity increase with the value of cone angle, which means the centrifugal force, also increases with the cone angle. The combination of large-angle cone and small-angle cone in a hydroclone is usually used to enhance the separation performance when the density difference of the two phases is too small.

4.2.3. Tangential velocity

Tangential velocity is the most important one among the three-dimensional velocities, which is one of the key indexes of the separation factor by determining the value of centrifugal force. It is because the tangential velocity is greater in value than the other two velocities, and what is more important is that, the centrifugal force deriving from the tangential velocity is the prerequisite for the separation of the two or more phases in hydrocyclones. Fig. 12 gives out the tangential velocity profiles in different cross-sections of hydrocyclones. The tangential velocity increases in the same direction with the reduction of radius from wall to axis. In the area near to the wall, the tangential velocity reaches its maximum and decreases with the reduction of radius until it reaching to zero in the central axis.

The cone combination has great influence on the value of tangential velocity. The maximum tangential velocity of hydroclone A is significantly higher than that of hydrocyclones B and C, and that of hydroclone B is slightly higher than that of hydroclone C. Thus, the variation of cone angles of a hydroclone influences the tangential velocity profile in that the tangential velocity increases with the angle of the first cone.

4.3. Capacity and flow split

The capacity and flow split were investigated under experimental method. The capacity is the volume flow of the feed, which is directly related to the inlet pressure of the solid–liquid hydroclone. It is an important factor for a hydroclone. When the inlet pressure is maintained constantly and the separation performance of hydroclone could meet the technological requirements, the larger the capacity of hydroclone the better. Under normal operating conditions, the capacity has a direct relationship to the pressure drops of inlet and overflow across the solid–liquid hydroclone. The relationship between the two pressure drops is also important and can be used for control purposes.

The effect of different cone combinations on the capacity is shown in Fig. 13. From Fig. 13, it can be seen that the volume flow of the feed increased with the increase of inlet pressure or the pressure
drop between inlet and overflow. The hydrocyclones with different cone combinations had basically the same capacities. The capacity was mainly related to the structural size of the hydrocyclone.

The relationship between pressure drop and the flow split of hydrocyclones is shown in Fig. 14. It can be seen that the flow split decreases with increasing the pressure drop. When the inlet pressure was larger than 0.2 MPa, the decrease of flow split became gentle as the pressure drop increased. This indicates that the increase of inlet flow has divided equally to the overflow and underflow outlet by a certain percentage. The cone combinations influenced the flow split of the hydrocyclone. When the angle of the second cone remained unchanged, the larger the angle of the first cone, the smaller the split of hydrocyclone.

4.4. Removal performance

The removal performance was also investigated under experimental method.

4.4.1. Separation efficiency

The inlet Reynolds number is a key factor and has significant effect on the separation efficiency of hydrocyclones. Fig. 15 shows the effect of inlet Reynolds number on the separation efficiency of hydrocyclones. It can be seen that the separation efficiency increases first and then decreases as the inlet Reynolds number increases. When the inlet Reynolds number is close to 85,000, the separation efficiency of hydrocyclone B first reaches maximum. The
The separation efficiency of hydrocyclone C reaches maximum when the inlet Reynolds number is close to 105,000, and the separation efficiency of hydrocyclone A reaches maximum when the inlet Reynolds number is close to 110,000. The maximum values of separation efficiency of hydrocyclones A, B, and C are 80%, 88% and 83%, respectively.

The different cone combinations have significant influence on the separation efficiency of hydrocyclones. On the one hand, the changes of two cone angles have the influence on high separation efficiency area of the hydrocyclone. The effect degree of the changes of two cone angles on the high separation efficiency area is in an order as follows: hydrocyclone B > hydrocyclone C > hydrocyclone A. The larger the two cone changes, the smaller the high separation efficiency area is. It is because every hydrocyclone with fixed angle of cone has maintained high separation efficiency area. The change of the cone angles results in the change of fluid flow inside the hydrocyclone, and consequently the change of the high separation efficiency area. The larger the change of cone angle, the smaller the overlap of high separation efficiency area is. On the other hand, the change of two-cone angle affects energy consumption in the hydrocyclone at the maximum separation efficiency. The energy consumption in the hydrocyclone is directly related to the inlet Reynolds number of the hydrocyclone. The bigger the inlet Reynolds number, the higher the energy consumption. The effect degree of the change of two cone angles on the energy consumption is in an order as follows: hydrocyclone A > hydrocyclone C > hydrocyclone B. The angles of the two cones change, the flow field inside the hydrocyclone changes. The larger the flow field inside hydrocyclone changes, the higher the energy consumption as a result.

4.4.2. Grade efficiency
The grade efficiency curves of hydrocyclones are shown in Fig. 16. It can be seen that the grade efficiency curves are “S”-like type. The sharpness of grade efficiency curve of hydrocyclone A is significantly lower than that of hydrocyclones B and C, and that of hydrocyclone B is slightly larger than that of hydrocyclone C. The cut size of hydrocyclones A, B, and C are almost the same. That is, the cone combination has little effect on the cut size.

The smaller the change of the angle between the two cones, the greater the sharpness of the grade efficiency curve; and vice versa. Higher sharpness of the grade efficiency curve is preferable in the classification process. The cone combination has impact on the separation efficiency of different particle sizes. Hydrocyclone A has significantly larger grade efficiency for the particles with size smaller than 15 μm compared with hydrocyclones B and C. Because the angle of the first cone of hydrocyclone A is much larger than that of hydrocyclones B and C, and the tangential velocity is much bigger than that of hydrocyclones B and C according to the simulation results, there are more small particles go into the next cone by the role of centrifugal force in hydrocyclone A. Therefore, it is better to use larger changes of two cones in the design of hydrocyclone, if focused on the uniformity of particle size separation process.

5. Conclusions
Simulate and experimental study of hydrocyclones with different cone combinations for solid–liquid separation and flow field inside hydrocyclones show that, the angle change of the cone has significant effect on the value of three-dimensional velocities, flow split, separation efficiency, energy consumption, and separation sharpness, but little effect on the distribution of pressure and that of three-dimensional velocities, the capacity and cut size. For solid–liquid separation, when the angle of the second cone does not change, the bigger the angle of the first cone, the smaller the split, the higher separation efficiency area, the bigger the pressure drop, and the stronger the centrifugal force. The smaller the angle of two cones changes, the larger the sharpness of the grade efficiency curve, and the less the energy consumption; and vice versa. If the angle of the first cone is much larger than that of the second cone, more small particles will be separated into the underflow.

Acknowledgments
We would like to express our thanks for the sponsorship of the New Century Excellent Talents in University (NCET-08-0777) and Innovative Fund (2008120613003).

References


