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STUDY ON IMPROVING THE CLASSIFICATION EFFICIENCY OF A LARGE-SCALE HYDROCYCLONE BASED ON CFD SIMULATION

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ABSTRACT

As the most important classification equipment in mineral processing industry, hydrocyclone has been studied widely. Diversified and large-scale hydrocyclones are necessary to meet the needs of present industrial production, but the following question is that the physical experimental studies on hydrocyclones become more difficult. Numerical simulation has been proved to be an effective method for the investigation of hydrocyclones because of its veracity, high efficiency and low cost. In this study, numerical simulation method based on Computational Fluid Dynamics (CFD) was used to improve the classification efficiency of a Φ660 mm hydrocyclone, which was used in the classification of a low-grade hematite ore in China. As the first step of model development, CFD model was set up and run using a scaled-down hydrocyclone (Φ50mm). In parallel, physical experiments facilitated with PIV flow field measurement and real mineral particles were conducted in the same sized hydrocyclone in order to validate the developed CFD model. Following model validation, the CFD model was extended to investigate the Φ660mm hydrocyclone. The classification efficiency was increased obviously by optimizing the operational and structural parameters of the hydrocyclone.

INTRODUCTION

Hydrocyclone has been widely used in many areas of separation due to the advantages of its low operating cost, high throughput, low space requirement, etc, and it's used almost in all of the mineral processing plants in the world. Multiple investigations on hydrocyclones have been carried out since the 1950s (Kelsall, 1952). Now a commonly accepted wisdom is that the separation characteristics of the hydrocyclone depend on the flow field, and turbulence intensity of which has a major impact on hydrocyclone's classification efficiency (Teja *et al*, 2014).

Classification efficiency is one of the most important parameters to evaluate the performance of a hydrocyclone. In mineral processing, consumptions of energy and steel balls can be decreased; capacity and separation can be increased via improving hydrocyclone's classification efficiency. Before the time when the importance of the internal flow field was formally recognised, design of a hydrocyclone was regarded as a 'black box'. Nowadays, the study of flow field inside hydrocyclone is a hot research area. The flow field in a hydrocyclone, which is characterized by a complex three dimensional swirling flow with an air core, is decided by various operational and structural parameters. Large-scale and strong turbulence is the main character of flow field inside hydrocyclone, local high turbulence intensity reduces the radial regular distribution of particles. The detailed velocity profiles in a hydrocyclone were measured first by Kelsall using a stroboscope (Kelsall, 1952). With the development of laser and high-speed camera technologies, laser Doppler velocimetry (LDV) and particle image velocimetry (PIV) are utilized to investigate the flow field inside hydrocyclones (Marins, 2010, Jonas and Hannes, 2004). Dabir and Petty (1984) measured the tangential and axial velocities in hydrocyclones using LDV as early as 1984. CFD simulation becomes an important numerical method for the detailed study of the flow field of hydrocyclones due to the rapid development of computer technology and mathematical models (Jose and Rajamani, 2005). The first successful CFD predictive work on hydrocyclones was reported by Rodes in 1987 (Rodes, *et al*, 1987). Nowadays, the CFD modeling software packages, including ANSYS/Fluent, have shown sufficient accuracy in modeling the flow field in a hydrocyclone, and simulation results have been compared with the LDV or PIV experimental measurement which demonstrated good agreement (Teja *et al*, 2014, Cui, *et al*, 2014).

In this paper, numerical simulation method based on CFD was used to improve the classification efficiency of a Φ660mm hydrocyclone, which was used in the classification of a low-grade hematite ore in China. As the first step of model development, CFD model was set up and run using a scaled-down Φ50mm hydrocyclone, using ANSYS/Fluent with a Reynolds stress model (RSM) for turbulence calculation, the volume of fluid (VOF) model for capturing the air-liquid interface, and a mixture model for predicting particle movement. In parallel, physical experiments facilitated with PIV flow field measurement that uses real mineral particles were conducted in the same sized hydrocyclone in order to validate the developed CFD model. Following model validation, the CFD model was extended to investigate the Φ660mm hydrocyclone. Turbulence intensity of the flow field was investigated to optimize the operational and structural parameters, the classification efficiency of the Φ660mm hydrocyclone was increased obviously.

MODEL DESCRIPTION

Hydrocyclone Geometry

Table 1 lists the parameters investigated in this study. The model as investigated in the experiment is based on a Φ50mm hydrocyclone.

Item	Φ50mm	Φ660mm
Feed pressure /MPa	0.1	0.1
Cone angle /°	15	20
Underflow outlet diameter /mm	8	100
Overflow outlet diameter /mm	15	200

Table 1: Parameters investigated in the study

Numerical model

Simulation of hydrocyclones requires accounting for the irregular interface between air core and the surrounding liquid, the turbulence induced by the strong swirling flow, as well as the movement behavior of particles. This has been a challenging task in the numerical modeling of multiphase flow.

In this paper, details of the modelling approach are not listed completely, only the key governing equations are briefly provided. For incompressible fluid, the equations for mass (or continuity) and momentum in a general form are as follows:

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

$$\rho(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j}) = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}[\mu(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}) - \rho\overline{u_i u_j}] + \rho g_i \quad (2)$$

The RSM model uses the following transport equation for the Reynolds stresses:

$$(\frac{\partial \overline{u_i' u_j'}}{\partial t} + u_k \frac{\partial \overline{u_i' u_j'}}{\partial x_k}) = \frac{\partial}{\partial x_k}(\frac{\nu_t}{\sigma_k}\frac{\partial \overline{u_i' u_j'}}{\partial x_k}) + P_{ij} + \phi_{ij} - \varepsilon_{ij} + R_{ij} + S_{ij} + D_{ij} \quad (3)$$

For VOF model, the governing equation for the phase i can be written as

$$\frac{\partial \alpha_i}{\partial t} + u\frac{\partial \alpha_i}{\partial x} = 0 \quad (4)$$

For the mixture model, the investigated mixed phase viscosity is closely related to the volume fraction of -10 μm as found in the physical separation test of a Φ50 mm hydrocyclone, the mixed phase viscosity μ_m is defined as follows (Chu, *et al*, 2012, Qi, *et al*, 2015):

$$\mu_m = 3.8\mu_w(1 - \frac{v_{-10\mu m}}{0.62}) \quad (5)$$

where μ_m is the water viscosity, and $v_{-10\mu m}$ is the volume fraction of -10μm particles.

Pressure inlet was set and assumed to be constant. Pressure outlets were set for overflow and underflow and assumed to be at atmospheric or zero gauge pressure. No-slip boundary conditions were applied on all walls. Initially, the whole fluid domain was assumed to be filled with air representing a startup condition of an actual operation.

Grid dependency studies were carried out, it was observed that 300,000 cells for Φ50mm hydrocyclone and 800,000 cells for Φ660mm hydrocyclone were optimal for compromised considerations of simulation accuracy and computing time. The meshes for the numerical simulation are shown in Figure 1.

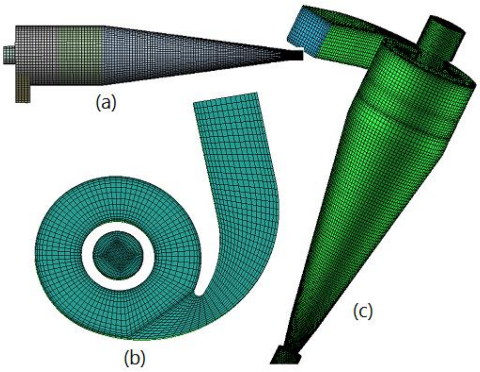


Figure 1: Meshes for numerical simulation
(a) Front view of the Φ50mm hydrocyclone; (b) Top view of the Φ660mm hydrocyclone; (c) 3D view of the Φ660mm hydrocyclone

Experimental model

To avoid complexities arising from testing of the full-scale hydrocyclone (i.e. Φ660mm),, physical experiments were performed for a scaled-down version of the unit (i.e. Φ50mm). Figure 2 shows photos of the experimental model. In order to reduce errors caused by laser scattering, a couple of orthogonal planes were placed in the outside of the transparent model.

(a) (b)

Figure 2: Experimental model
(a) hydrocyclone for PIV measurement; (b) hydrocyclone for real mineral particles

Polystyrene powder (-10μm, 1050kg/m^3) was used as tracer particle in the PIV measurement, which was carried out to obtain the flow velocities over a vertical plane passing the hydrocyclone centre axis. A total of 200 transient velocity frames were recorded to obtain a time averaged value.

Quartz particles (2673kg/m^3) were fed into the Φ50mm hydrocyclone, the size distribution is shown in Table 2.

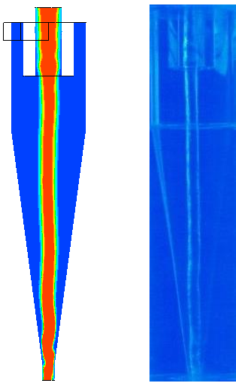
Particle size /μm	Yield /%
-70+55	8.69
-55+30	17.78
-30+20	34.18
-20+10	50.21
-10+5	72.2
-5+2	79.03
-2	100.00

Table 2: Size distribution of mineral particles used in this paper

RESULTS AND DISCUSSION

Model Validation

The air core as predicted and measured inside the Φ50mm hydrocyclone is compared in Figure 3, and axial velocity distributions along a horizontal symmetry axis at the lower end of the cylindrical section (or upper end of the conical section) of the hydrocyclone are also compared in Figure 4. Results obtained by both numerical and experimental methods are in very good agreement.



(a) (b)

Figure 3: Comparison of air core
(a) CFD simulation; (b) physical measurement

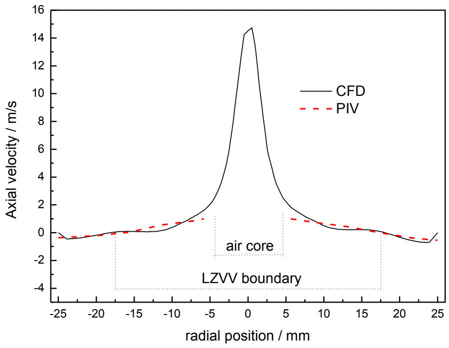


Figure 4: Comparison of axial velocity distributions

When solids volume fraction of the feeding particles was 10%, Φ50mm hydrocyclone classification tests of quartz particles were carried out by both numerical and physical methods. Size distributions of underflow products were compared in Figure 5. For the physical experiment, results were averages based on five tests. It can be seen that the mixture model as given in equation (5) has sufficient accuracy.

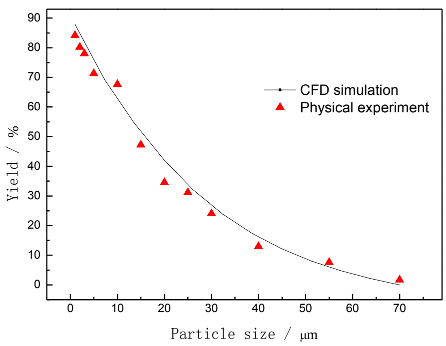


Figure 5: Comparison of size distributions of underflow products

Investigation of Φ660mm Hydrocyclone

The Φ660mm hydrocyclone is being used in the classification of a low-grade hematite ore in China, the size distributions of feeding and products are shown in Table 3.

Particle size /μm	Feeding /%	Overflow /%	Underflow /%
-250+154	6.72	0.20	9.51
-154+100	29.48	2.88	40.87
-100+71	42.86	10.76	56.61
-71+45	65.60	32.28	79.87
-45+36	73.01	41.09	86.69
-36+25	79.63	53.22	90.94
-25+10	89.95	76.17	97.55
-10	100.00	100.00	100.00

Table 3: Size distribution of feeding and products of Φ660mm hydrocyclone

Classification efficiency of the hydrocyclone E can be obtained by:

$$E = \frac{(\alpha-\theta)(\beta-\alpha)}{\alpha(\beta-\theta)(100-\alpha)} \times 100 \qquad (6)$$

where α, β and θ are proportions of particles for a particular size group in feeding, overflow and underflow respectively. Table 3 shows that the classification efficiency of -71μm particles is as low as 39.32%, and the main reason can be obtained from Table 3 is that there are too many -71μm particles entering the underflow. It's necessary to reduce the yield of -71μm particles in the underflow to increase the classification efficiency. Effective methods include increasing the cone angle and overflow outlet diameter, and decreasing feed pressure and underflow outlet diameter.

Figure 6 shows turbulence intensity of the flow field with different cone angles. With the use of a 25°conic section, the turbulence intensity reduces generally, which is useful for improving the classification efficiency. The turbulence intensity increases around underflow outlet. This is helpful for removing the fine particles before they enter the underflow. The underflow outlet diameter of 80mm and overflow outlet diameter of 210mm are determined based on the same method.

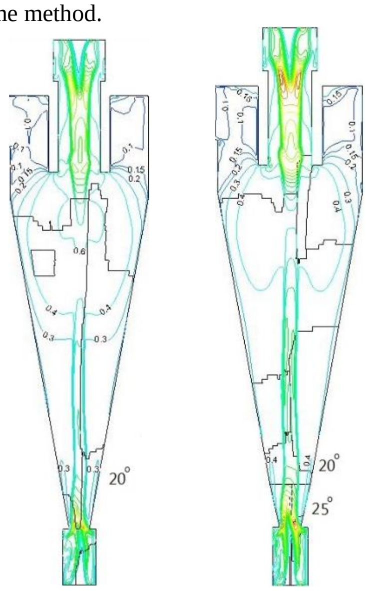


Figure 6: Turbulence intensity of the flow field with different cone angles

In this study, the reduction of feed pressure can not only increase the classification efficiency but also reduce the energy consumption. However, there is a minimum feed pressure to maintain the stability of the hydrocyclone. It can be seen from Figure 7, the air core for feed pressure 0.04MPa shows significantly different pattern from others, feed pressure 0.06MPa is recommended in this case.

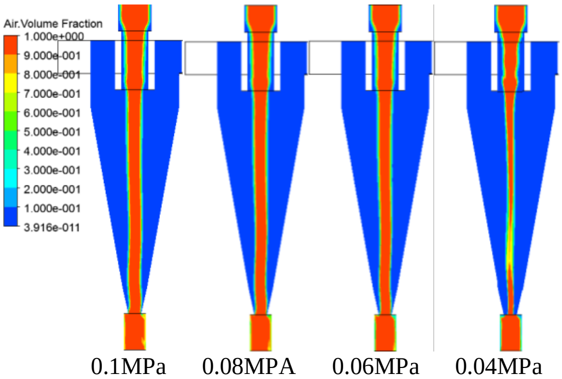


Figure 7: Air core pattern for different feed pressure

For a solids volume fraction of 10% (feeding), feed pressure 0.06 MPa, cone angle 1st 20° and 2nd 25°, underflow outlet diameter of 80 mm and overflow outlet diameter of 210 mm, solids volume fraction distributions for different particle sizes are shown in Figure 8. For convenience of calculation, the densities of different particles were set according to their respective iron grade. Density calculation equation is as follows:

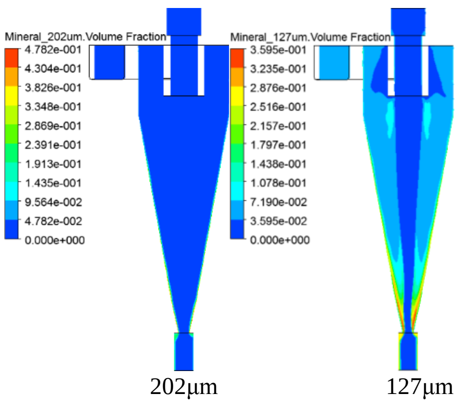
$$\rho = \frac{100}{38.5 - 0.265\beta} \quad (7)$$

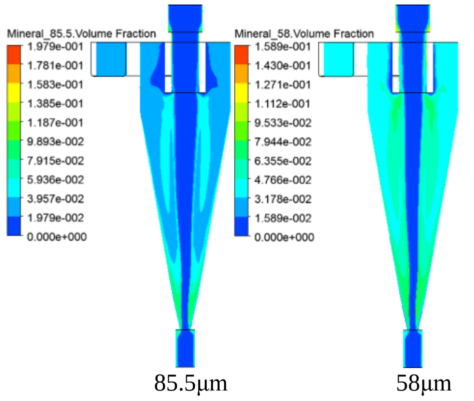
Where β is the iron grade of a particular size particles in feeding, details of which are shown in Table 4.

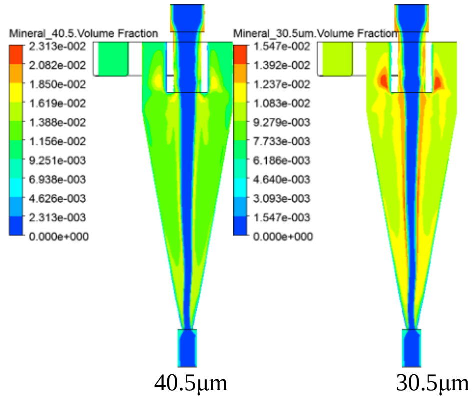
Particle size /μm	Iron grade /%
-250+154	18.23
-154+100	20.82
-100+71	34.77
-71+45	47.20
-45+36	50.47
-36+25	49.83
-25+10	39.84
-10	38.95

Table 4: Iron grade distributions

According to the CFD simulation results, classification efficiency for -71μm particles is about 47.54%, industrial test will be performed to validate the numerical result.







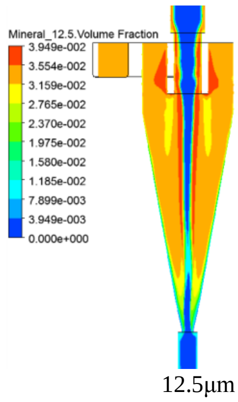


Figure 8: Solids volume fraction distributions for different particle sizes in the new Φ660mm hydrocyclone

CONCLUSIONS

Flow dynamics and particle separation in hydrocylones of Φ50mm and Φ660mm have been numerically studied using CFD models with ANSYS/Fluent being a numerical platform. The main findings from the present work are:

1) Using a Φ50mm hydrocyclone as a testing bed, CFD simulation results agreed well with physical experimental results in terms of air core size, liquid axial velocity distribution and particle separation. The good agreement demonstrates validity of the present modelling approach for hydrocylone studies, e.g. RSM and VOF models for predicting the air core formation and the corrected Mixture model for the description of particles movement behaviour.

2) Large-scale and strong turbulence is the main characteristic of flow field inside hydrocyclone. The classification efficiency of hydrocyclone can be improved through reducing the turbulence intensity of flow field inside hydrocyclone by optimizing the operational and structural parameters.

3) For the Φ660mm hydrocyclone, the classification efficiency for -71 μm particles in the original design is as low as 39.32%. According to numerical results, when feed pressure 0.06MPa, cone angle 1st 20° and 2nd 25°, underflow outlet diameter 80 mm and overflow outlet diameter 210 mm, the classification efficiency of -71 μm particles can be up to about 47.54%.

The simulation results demonstrated that CFD model is a valuable research tool in improving research efficiency of hydrocyclone. The usefulness of CFD model will be fully demonstrated in the future for a detailed evaluation of the design and/or operations of industrial scale hydrocyclones of various types.

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