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Numerical simulation of flow field in enhanced gravity concentrator

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Abstract: Enhanced gravity concentrator have excellent separation accuracy for the fine mineral particles. However, its internal flow characteristics are still in unclear. Therefore, numerical simulation was conducted to study the flow characteristics of concentrator. Effect of centrifugal force and fluidization water pressure on the velocity component of fluid was studied. The simulation accuracy was verified by the theoretical calculation. The turbulence intensity in the radial direction was analyzed to reveal the gradient characteristics. Results show that the three-dimensional velocity has different order of magnitude. The increase of centrifugal force significantly improves the three-dimensional velocity of fluid. However, the fluidization water pressure has little influence on the tangential velocity and axial velocity, but it can effectively improve the radial velocity. High turbulent flow energy and high turbulence dissipation rate are presented in the near wall region, which allows the light particles reentering the separation region. Meanwhile, the fluid presents stable flow pattern in the fall wall region that is conducive to the stratification process. In addition, the increase of centrifugal force increases the turbulence in the near wall region; however, fluidization pressure has no effect.

Keywords: enhanced gravity concentrator, numerical simulation, three-dimensional velocity, turbulence characteristics

1. Introduction

Gravity separation has been proved to be low cost, high efficiency and environmental friendly technology for the beneficiation of fine materials. As for fine coal, sedimentation velocity difference is not significant in gravity field, resulting in poor separation efficiency. Therefore, the method of using centrifugal force to accelerate the particle settling has been proposed. Under the action of centrifugal force, settling velocity increased significantly, which lead to reduction of minimum separation size while the processing capabilities of the device are improved (Tao et al., 2006).

In the past few decades, the separation theory of flowing film has been gradually improved on the basis of a great quantity of experimental data. In spite of this, it is still lack of effective means to verify the theoretical analysis (Majumder et al., 2006; Kroll-Rabotin et al., 2010; Kroll-Rabotin et al., 2012). The indisputable fact is that internal flow characteristic has a vital impact on the separation efficiency. Ascertaining the distribution of flow field characteristics, including velocity distribution, velocity gradient and flow film thickness, has important significance on understanding the separation process. However, the separation mechanism of the centrifugal separator is still in the "black box", and the existing operation and improvement are all experienced, which seriously hinders the optimization of the mechanical.

In previous studies, basic dynamics research of particles in centrifugal field and massive laboratory tests have been carried out. Centrifugal concentrator, including Knelson separator and Falcon separator, has been widely used for the beneficiation process of fine metal minerals and fine coal (Liu et al., 2006;

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Majumder et al., 2006; El-Midany and Ibrahim 2011; McGrath et al., 2013). Excellent deash and desulfurization efficiency of fine coal was obtained in centrifugal field (Honaker et al., 2005; Majumder et al., 2007; Oruç et al., 2010; Zhang et al., 2011; Uslu et al., 2012; Ibrahim et al., 2014). However, the internal flow characteristics of the centrifugal separator are seldom studied. Non-contact observation is the most direct and effective method for the study of the flow field. The above research ideas are difficult to be realized based on the existing technology because of the high speed, the thin film thickness and the complex flow field in enhanced gravity concentrator. With the development of high performance computing and the theory of turbulence model, numerical simulation has become one of the main methods to study the flow field in the centrifugal field, which is seldom involved in previous studies.

Thus, the purpose of this paper is to study the flow field characteristics in centrifugal concentrator, which is validated by high-speed dynamic shooting. In this paper, 3D model of the Falcon concentrator was first established, then flow characteristics under different operating parameters were simulated. Furthermore, the influences of key operating parameters on the three-dimensional velocity field of fluid were analyzed. In addition, the radial turbulence characteristics of the separation zone are also analyzed to reveal the gradient characteristics of the separation process.

2. Materials and methods

2.1 Numerical methods

As shown in Fig. 1, the 3D model of the Falcon concentrator was established by Solidworks software according to the entity structure parameters of separator. The model was introduced into the ICEM software to mesh. Unstructured tetrahedral mesh was used. Mesh in recoil holes and complex structure of the rotor were intensified as shown in Fig. 2. There are two inlets. Bottom surface of central cylinder is inlet 1. Fluid enters into the separation chamber under gravity at the inlet 1. Meanwhile, inlet 2 is the recoil hole with number of 86, recoil water velocity was controlled by regulating the inlet pressure. The top surface of the concentrator subtracts top surface of central cylinder inlet 1 is set as outlet. The total grid number is 1,020,000. In this part, liquid was modeled using the continuum model. The models used in the simulation are all the existing models in the software.

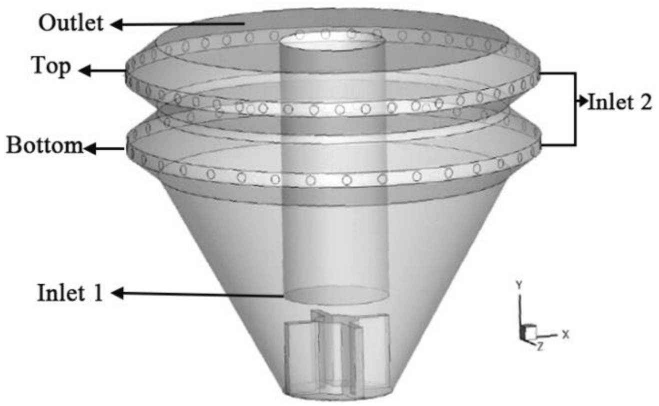

Fig. 1. Geometric model of concentrator

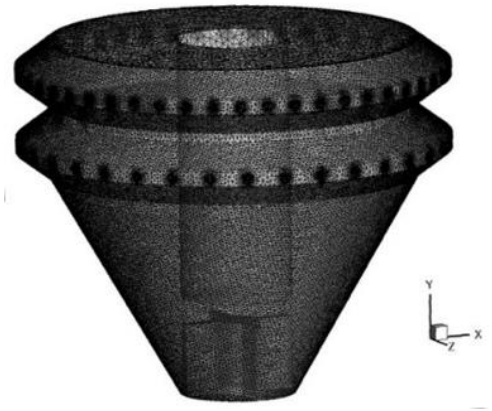

Fig. 2. Mesh of Falcon concentrator

2.2 Analysis of flow field characteristics

In this paper, the complex flow field consisting of centrifugal force and fluidization water was studied by using the numerical calculation method of CFD multiphase flow from the macro and micro level. The tangential velocity, axial velocity and radial velocity of the fluid were analyzed in detail. The influence of the centrifugal force and fluidization water pressure on the three-dimensional velocity of fluid was analyzed. In addition, the turbulence characteristics of the flow field in the separation region were analyzed by the microscopic kinetic parameters of turbulent kinetic energy and turbulent dissipation rate. Therefore, the gradient sorting characteristics along the radial direction were analyzed.

3. Results and discussion

3.1 Accuracy analysis of numerical simulation

In order to analyze the accuracy of numerical simulation in the separation zone, the theoretical calculation method was used to obtain the radial velocity of the fluid. The specific derivation process is detailed in previous paper (Zhu et al., 2017).

$$v_n = \frac{V_B}{2\pi r_n\left[2(r_0 - r_n)\tan\alpha + l_0\right]} \tag{1}$$

In the equation, v_n is radial velocity at a given position, V_B is the fluid volume per unit time, r_n is the radial distance from given position to axis, r_0 is the radial distance from bottom of separation chamber to axis, l_0 is width of bottom of sorting chamber, α is the inclination of separation chamber. V_B is measured by experiment, other values are fixed values under certain conditions. Comparison results are shown in Fig. 3.

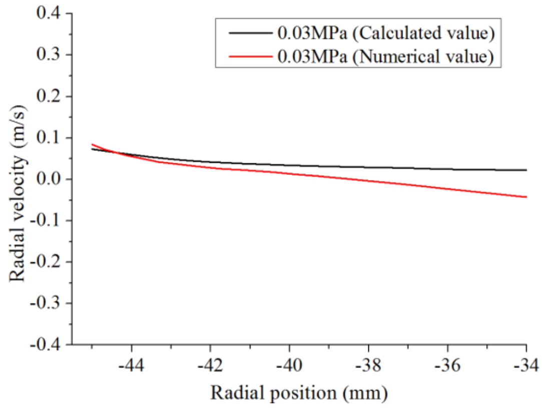

Fig. 3. Simulation accuracy analysis of the separation zone (radial velocity)

Fig. 3 illustrate the radial velocity of fluid obtained by calculated and numerical simulation are both reach the precision of centimeter-level. In addition, radial velocity shows a slowly increasing trend in the radial direction, which is determined by the trapezoid structure of the separation chamber. Thus, it can be concluded that the numerical simulation has reached high simulation accuracy, and the numerical simulation results will be used to analyze the flow field in the separator.

3.2 Analysis of flow field characteristics

3.2.1 Influence of centrifugal force on fluid velocity

Numerical simulation results that influence of centrifugal force on the tangential velocity, axial velocity and radial velocity in the bottom groove are shown in Fig. 4.

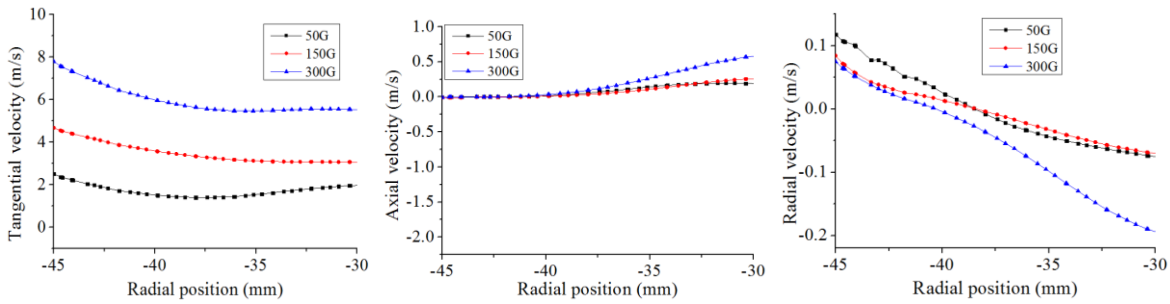

Fig. 4. Influence of centrifugal force on the three-dimensional velocity

It can be seen that centrifugal force has great influence on the velocity distribution of flow field. The similarity law is that the velocity component in three directions increases with the increase of the centrifugal force. The tangential velocity is much greater than the axial velocity that is greater than the radial velocity. As for tangential velocity, greater tangential velocity can drive the particles to move at higher speeds. It should note that great velocity gradient is observed at near wall region because of the disturbance caused by fluidization water. In addition, according to the separation theory of Bagnold, shear stress in the inertia regime depend quadratic on shear rate. Meanwhile, the normal stress is proportional to the shear stress. That is, the greater centrifugal force can cause normal stress. The radial velocity of the fluid determines the sedimentation process of materials at separation zone. It is necessary to find the suitable axial velocity to realize the optimal combination of separation precision and energy consumption. The stratification and separation process of particles usually occurs in the radial direction, and adaptive radial velocity can provide conformable drag force, which can achieve the balance of the recovery and grade.

3.2.2 Influence of fluidization water pressure on fluid velocity

Numerical simulation results that influence of fluidization water pressure on the tangential velocity, axial velocity and radial velocity are shown in Fig. 5.

Obviously, fluidization pressure has little effect on the tangential velocity of the fluid, and the difference is only in the range of 35-30 mm, which shows a slight decreasing trend with the increase of fluidization pressure. In addition, fluidization water pressure has almost no effect on the axial velocity because there is no significant difference in the axial velocity in the radial direction. However, radial velocities at different fluidization water pressure are showing a significant difference. That is, radial velocity increases with the fluidization water pressure. This phenomenon indicates that the higher fluidization pressure can provide larger radial velocity, which makes the particles difficult to capture. Similarly, tangential velocity is much greater than the radial velocity and axial velocity.

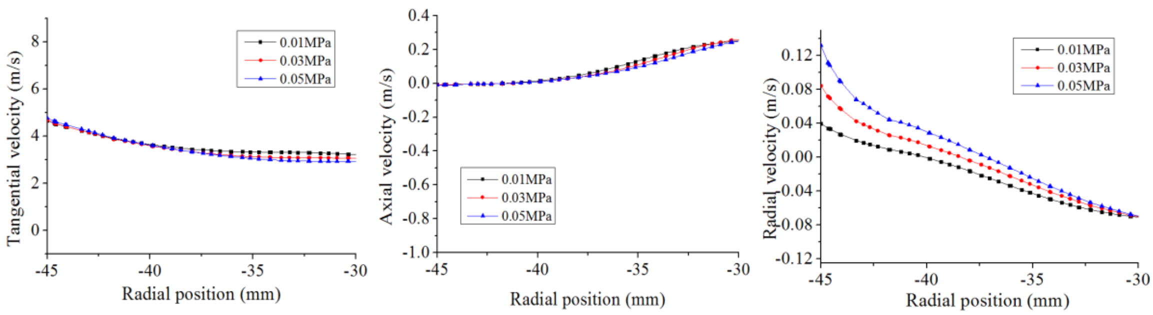

Fig. 5. Influence of fluidization water pressure on the three-dimensional velocity

3.2.3 Turbulence characteristics in separation region

The study of turbulent characteristics of particles (0.35mm, 1250Kg/m^3) in the flow field is helpful to analyze the separation characteristics of particles in the separation area. The turbulent field is composed of different scales of vortex. Turbulent kinetic energy and turbulent dissipation are commonly used to characterize large scale eddies and small-scale eddies respectively. The results are shown in Fig. 6. The influences of key operating parameters on the turbulent characteristics are analyzed as follows.

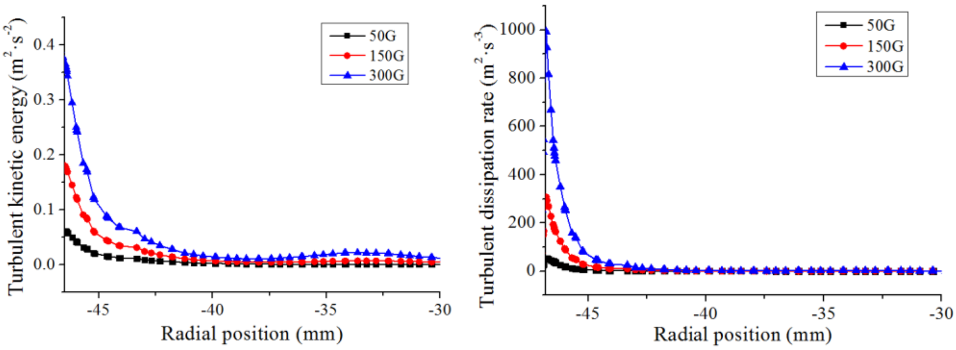

Fig. 6. Effect of centrifugal force on radial turbulence

Fig. 6 illustrate the near wall region presents a significant turbulence characteristic. However, the flow field in the far wall region exhibits quasi laminar characteristic. In the quasi laminar separation environment, the fluid state is stable and the disturbance is small. In the near wall region, the turbulent energy is reflected in the high turbulent kinetic energy and dissipation. Particles are fully dispersed due to the anisotropic turbulence, the mismatch particle, that is the low-density particles in this area caused by the entrainment effect are washed and re-entering the separation region, which helps to improve the sorting accuracy of high sorting process. Because of the fluid following of ultrafine particles, it is not conducive to the separation of fine particles in the turbulent region.

Fig. 6 also shows that the centrifugal force increases the turbulent characteristics of the near wall flow field, but the change of the centrifugal force does not affect the turbulence characteristics of the far wall. The turbulent kinetic energy and turbulent dissipation rate are close to zero in the far wall area, which proves the laminar flow characteristics of the main separation flow field.

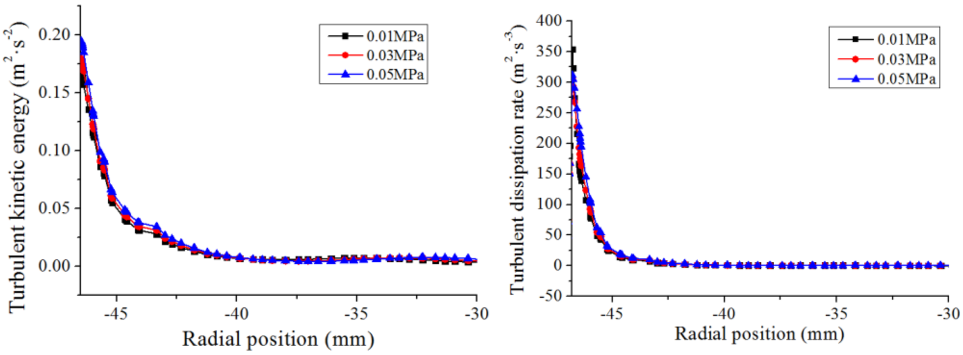

Fig. 7. Effect of fluidization water pressure on radial turbulence

Fig. 7. shows that with the increase of fluidization water pressure, the turbulence characteristics of the separation area are almost unchanged, and the effect of fluidization pressure on the turbulence intensity is slight. Therefore, the centrifugal force is the main factor that causes the turbulence characteristics of the flow field.

The flow pattern of separation environment is the key to realize the efficient separation of fine particles in the composite force field. In the separation region along the radial direction, the centrifugal force and the fluidization water constitute the turbulent flow field-quasi gradient layer flow separation characteristics, momentum transfer is realized by using turbulent flows and strengthen the precise sorting of particles.

4. Conclusions

Characteristic of the complex flow field has an important influence on the separation mechanism and efficiency in the enhanced gravity concentrator with high speed swirling. In view of the small space and complexity of the flow in the laboratory concentrator, the traditional contact method is not feasible to get the flow field. Thus, numerical simulation was used to study the flow field characteristics of concentrator in this paper.

Three-dimensional numerical calculation of single flow field was completed. The flow characteristics of the fluid in the separation region were obtained. The influence of two key factors, the centrifugal force and the fluidization water pressure, on the fluid velocity was studied. Results show that the tangential velocity of fluid in the separation area is greater than the axial velocity that is greater than the radial velocity. The increase of centrifugal force significantly improves the three-dimensional velocity of the fluid. However, the fluidization pressure has little influence on the tangential velocity and axial velocity of the fluid, but it can effectively improve the radial velocity of the fluid.

The turbulence characteristics of the flow field in the separation area were analyzed. In the near wall region, the characteristics of high turbulent flow energy and high turbulence dissipation rate are presented. Due to the anisotropic turbulence, the strong turbulence characteristics dispersed particles in the near wall region, and the mismatch particles re-entering the separation region, which is conducive to the precise selection process. In the far wall region, i.e., in the main area of separation, the value of the two is close to zero. The fluid presents stable flow pattern, and the stable separation environment is helpful to the process of fine particle stratification. The effects of centrifugal force and fluidization water pressure on the turbulent characteristics were analyzed. Results show that the increase of centrifugal force increases the turbulence in the near wall region. However, fluidization pressure has no effect.

Acknowledgments

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