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The Numerical Simulation Study on the Forward-flow Cylindrical Hydrocyclone Field

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Abstract

The Forward-flow cylindrical hydrocyclone (FFCH) can be applied to the sorting of the minerals and the classification of particles, but the separation is inefficient. By using the FLUENT software to simulate FFCH flow field, the result illustrates that the RSM can be used to accurately calculate the flow field of the structure. And the tangential velocity is in good agreement with the reference materials. The tangential velocity has the characteristics of the combination of the forced vortex and quasi-free vortex. The axial velocity shows that there is a swirl in the longitudinal direction. The larger centripetal radial velocity mainly appears near the entrance and the underside of the classifier. Improvement of the classification efficiency can be achieved by increasing the density of liquid, reducing the inlet velocity, increasing FFCH diameter, changing the structure size and position of FFCH outlet, adding the auxiliary parts.

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Keywords: *forward-flow, cylindrical hydrocyclone, simulation, systematics;*

1. Introduction

Particle classification is a common process; cyclone is a kind of equipment that can be used in the process according to the particle size. In the reference[1], a Forward-flow cylindrical hydrocyclone is introduced. The device sets the discharging outlet at different positions (the radius) .Tests on the classification performance of the Forward-flow cylindrical hydrocyclone were performed in the reference[2].The result shows that the separation efficiency of

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the Forward-flow cyclone[3] FFCHA-1000 is higher than of the conical cylindrical hydrocyclone HC-900. In this paper, the computational fluid dynamics software FLUENT6.3 is used to study the flow field characteristics and classification performance of the Forward-flow cylindrical hydrocyclone.

2. Simulation methodology

The flow inside a hydrocyclone is characterized by an inherently unsteady, highly anisotropic turbulent field in a confined, strongly swirling flow. Turbulence models based on higher-order closure, like the Reynolds stress model (RSM) along with unsteady Reynolds averaged Navier–Stokes (RANS) formulation showed good prediction capabilities (Slack et al.[4], Wang et al.[5]). Further, the results of previous CFD simulation work carried out by authors on hydrocyclone using RSM had proven better results. Turbulent flow inside a hydrocyclone is anisotropic in nature, hence within the framework of RANS family, Reynolds stress model (RSM) which is reported to predict turbulence behavior inside a cyclone with a better accuracy was chosen. The RSM was proven to be an appropriate turbulence model for cyclone flow, although it is computationally more expensive. The governing equations for an incompressible fluid can thus be written as[6]:

$$\frac{\partial p}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho u_i\right)=0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho u_i\right)+\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_i}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_i}\right)\right]+\frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right) \tag{2}$$

Eqs. (1) and (2) are called Reynolds-averaged Navier–Stokes (RANS) equations. They have the same general form as the instantaneous Navier–Stokes equations, with the velocities and other solution variables representing ensemble-averaged (or time-averaged) values. Additional terms represent the effects of turbulence. These Reynoldsstresses include turbulence closure, $R_{ij}=\left(\rho u_i' u_j'\right)$ must be modeled in order to close Eq. (2). In Reynolds averaging, the solution variables in the instantaneous Navier–Stokes equations are decomposed into the mean (ensemble-averaged or time-averaged) and fluctuating components. For the velocity components:

$$u_i=\overline{u}_i+u_i' \tag{3}$$

where $\overline{u}_i$ and u_i' are the mean and fluctuating velocity components (i=1,2,3).
Likewise, for pressure and other scalar quantities:

$$\varphi=\overline{\varphi}+\varphi' \tag{4}$$

where φ denotes a scalar such as pressure, energy, or species concentration.

The laboratory equipment is taken as a research object in the reference[1]. The equipment structure is shown in Figure 1; the sizes are shown in Table1. GAMBIT software is used to make the model and mesh according to Table1; the model is shown in Figure 2.The grids generated are all structured, and the grid number is 17234. Numerical simulation of the model is carried out using the computational fluid dynamics software FLUENT6.3. RSM is used as a calculation model; the single-phase flow field is calculated under the steady-state condition. The medium is the liquid water. The solver algorithm is the SIMPLEC. The pressure option is PRESTO, the precision is QUICK. The boundary conditions are as follows: the velocity inlet, v_i =1.84 m/s, the pressure outlet, the gage pressure is 0 Pa. DPM is adopted to simulate the motion of particles. The parameter settings of the DPM are as follows: the density of solid particles is 2400 kg/m^3, the minimum particle size is 0.005 mm, the maximum particle size is 0.005 mm, the average particle size is 0.038 mm and the inlet velocity is 1.84 m/s.

Table.1 Structure sizes of FFCH (mm).

D	L	R_1	R_2	R_3	d_i	d_1	d_2	d_3
125	115	53	35	10	22	7	7	7

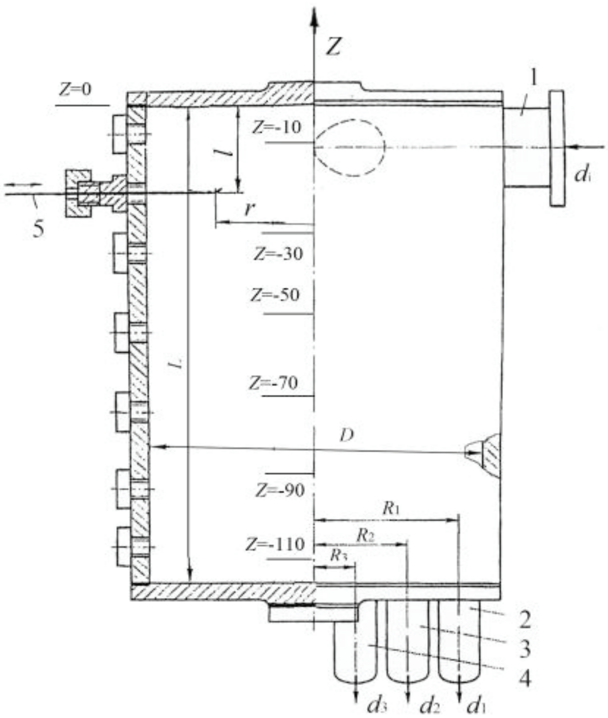

Fig.1 The structure of FFCH

1-inlet 2,3,4-discharging outlet 5- the sensor

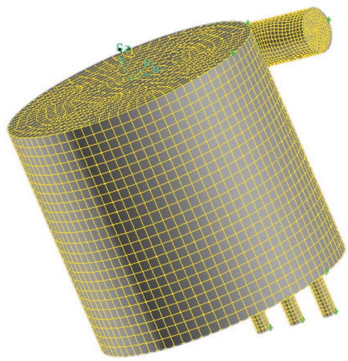

Fig.2 The grid structure of FFCH

3. The simulation results analysis

(1)The velocity distribution

The tangential velocity of the plane $Z = -70$ mm ($l = 70$ mm) is given in the reference[1] as is shown in Figure 3. In Figure 3 the tangential velocity of single-phase steady state is drawn using the RSM. It is obvious that the results by the RSM calculation are slightly lower than the experimental value in the center area where the radius is less than 15mm. And in the area where the radius is larger than 15mm, the simulation results agree well with the experiments. So, the RSM model can accurately calculate the characteristics of flow field and the particle movement rule in the FFCH.

The tangential velocity is the key parameter in the hydrocyclone separation. The tangential velocity is calculated at different positions of the Z axis which is shown in Figure 4. The tangential velocity has the form of the combination of the forced vortex and the quasi free vortex, which is similar to the conventional tube-cone cyclone. Among them, the tangential velocity of the plane Z=-10mm and Z=-30mm reaches the maximum at the position where X=-60mm, and drops toward the center, which presents a different rule from other places. It is because this is the height the cyclone entry is corresponding to; the feeding rate is high that drives the liquid near the wall rotating with high speed together. The zero position of the tangential velocity at each section is different, which illustrates that the center of rotation is not always at the geometric center of the device and changes.

In addition, with the decrease of the height in Z axis, the tangential velocity has no obvious attenuation. The tangential velocity presents an asymmetry phenomenon. The maximum of the tangential velocity appears within the radius of 25 to 30 mm, and the maximum value is about 1.5 m/s that gradually decrease outward along the radius.

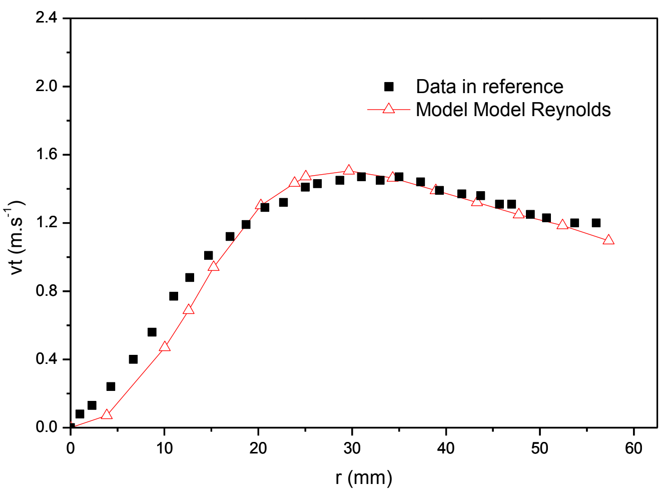

Fig.3 The tangential velocity of the plane Z=-70mm.

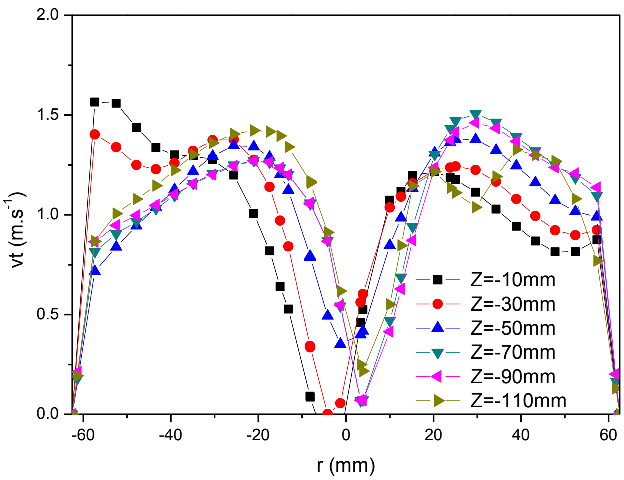

Fig.4 The tangential velocity at different positions of the Z axis plane.

The distribution of the axial velocity is shown in Figure 5. It is evident from Figure 5 that the fluid on the right side of the X axis flows down, and the fluid on the left side flows up; a huge vortex is produced at the vertical direction. This is because the outlet area is smaller than the inlet area; the fluid cannot be discharged in time because all three discharging outlets are in the direction of increasing X, the fluid on the right side goes down. The three low points on the right side of the axial velocity curve of Z=-110mm react on the position of the three discharging outlets. Figure 5 also illustrates that the axial velocity curve near the right side of the wall gradually reduces with the decrease of the height, which shows that the discharging flow of the outlet 1 is the biggest.

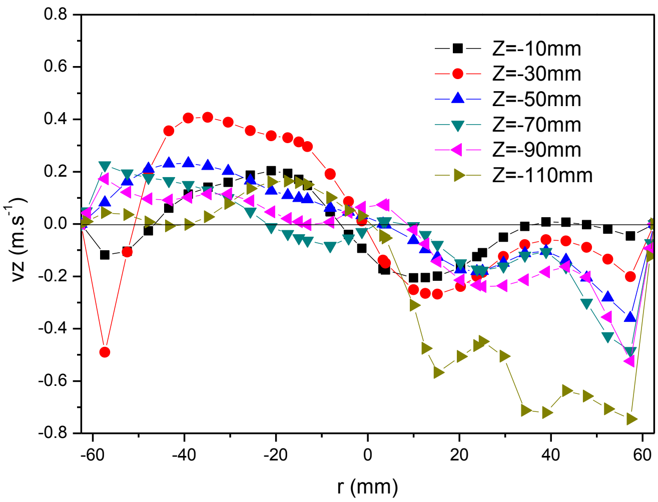

Fig.5 The distribution of the axial velocity at different positions of the Z axis plane.

The radial velocity distribution is shown in Figure 6. The radial velocity is larger at the top of the inlet area (Z=-10mm，Z=-30mm) and the bottom area (Z=-110mm). The radial velocity of the bottom area is affected by the discharging outlet. The radial velocity in the middle of the area is very small. The flow field is different from the field of the conventional hydrocyclone. This is because part of the liquid in the conventional hydrocyclone needs to move to the upward flow area of the center and flows out from the overflow mouth; the radical velocity is higher and on average relative to FFCH.

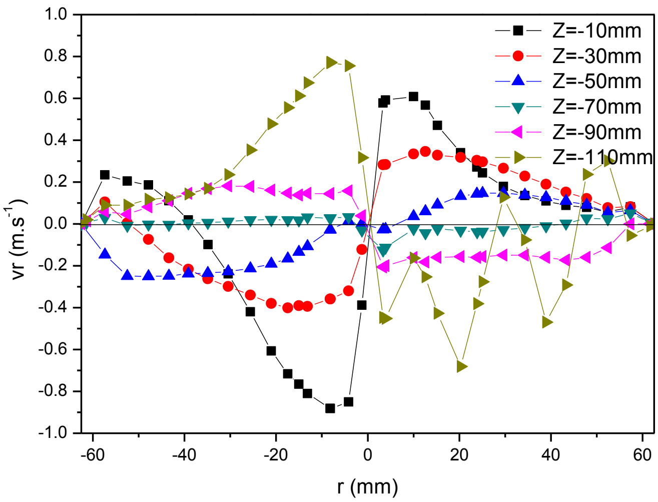

Fig.6 The radial velocity distribution at different positions of the Z axis plane.

(2) The pressure distribution

The pressure distribution rule of FFCH presents a parabolic shape, which is similar to the one of the conventional hydrocyclone. In the radial direction, the pressure increases gradually outwards along the radius from the center. In the axial direction, the pressure reduces with the decrease of the height gradually, and reaches the minimum value at the three discharge outlets. The pressure of three discharging outlets is different, so the outlet velocity is different. The simulation results show that the fluid velocity of the three discharge outlet 1, 2, 3 is 1.14 m/s, 1.10 m/s, 1.00 m/s, respectively.

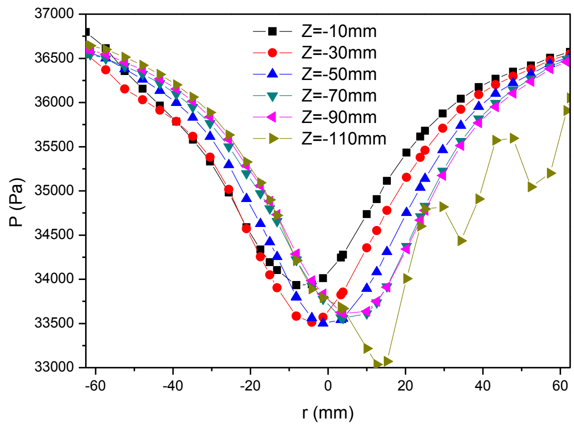

Fig.7 The pressure distribution rule at different positions of the Z axis plane.

(3) Particle movement rule

The particle mass concentration distribution is shown from Figure 8 to Figure 10 after the particles moving for 2 seconds. It can be seen from Figure 8 that the flow of the most of particles is a spiral downward movement with the liquid and in belts. From Figure 9, the concentration distribution of plane Y=0, particles are mainly concentrated in the wall and near the bottom; there are almost no particles in the center area, which is very bad for the particle classification. From the particle concentration distribution at the bottom of Figure 10, it reflects that particles do the spiral movement with the fluid at the bottom and flow out from the discharging outlet. Part of the particles has been separated in the process above. From the point of the outlet, particle size distribution occurs, though the particle number of three outlets is different, the volume fraction of the different particle size is similar, the classification efficiency is not ideal.

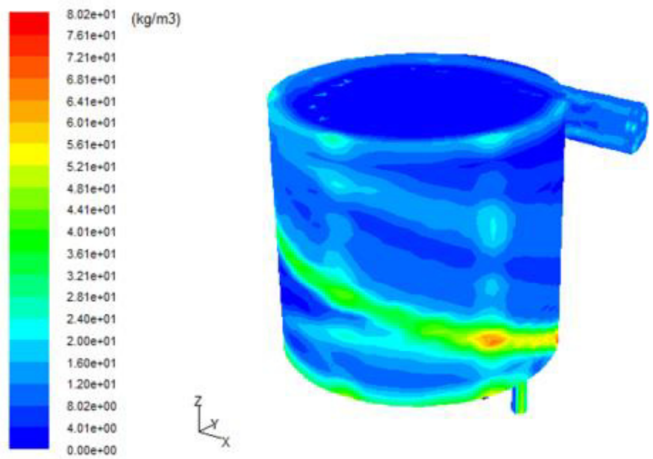

Fig.8 Particle mass concentration distribution of the FFCH wall.

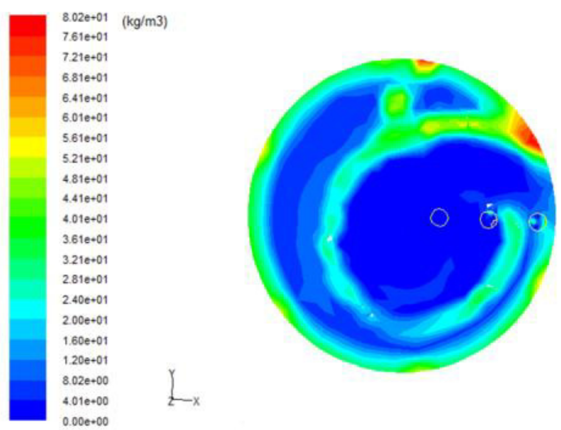

Fig.9 Particle mass concentration distribution of the FFCH bottom.

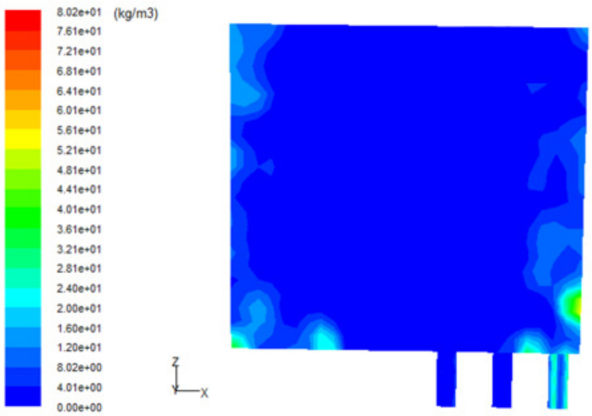

Fig.10 The average particle mass concentration distribution of FFCH at Y=0mm.

Solid particles in radial direction is mainly affected by the centrifugal force F_C pointing to the cyclone wall, centripetal buoyancy F_B pointing to the center and fluid drag force F_D to the heart in the cyclone. The resultant force of F_C and F_B is:

$$F_C - F_B = \frac{\pi d^3 (\rho_s - \rho)}{6} \frac{v_t^2}{r} \tag{5}$$

In the formula, d is the diameter of solid particle; ρ_s and ρ are the solid particles and liquid density, respectively.

The radial movement of solid particles and fluid is generally regarded as a laminar flow state. So, the flow resistance F_D on particles in radial can be expressed as[7]:

$$F_D = 3\pi\mu d \Delta v_r \tag{6}$$

In the formula, μ is the liquid viscosity, d is the diameter of the particles, Δv_r is the relative velocity between solid particles and liquid.

The ideal condition of the classification of particles is that the particles are distributed at the position of different radius according to the particle size. When $\rho_s > \rho$, the centrifugal force acting on the particles points in the direction of the cyclone wall. As the radial velocity in the most area of this equipment is very small, the centripetal drag force F_D decreases. Particles cannot move to the center to complete the distribution of the different particle size, so the equipment cannot work well in the classification.

In order to achieve the purpose of the particle classification, several aspects can be done as following:

a) Increase the liquid density, reduce the density difference between particles and fluid, so as to reduce the centrifugal force acting on particles;

b) Reduce the inlet velocity or increase the diameter of FFCH to reach the purpose of reducing the tangential velocity, then reducing the centrifugal force;

c) Change the flow field of FFCH; especially change the distribution of radial velocity. For example, increase the discharging outlet diameter in the center of the area, change the distribution of discharging outlet flow, increase the radial velocity of the fluid;

d) Add auxiliary parts. Design the ring baffles with different diameter according to the discharging outlet diameter[2]. Its principle is that the particles fall into outer ring area of the bottom along the cylinder wall; the large size particles are intercepted by the ring baffles, remain in the outside ring area and are discharged. The small size particles flow through the ring baffles and move into the central area, so as to realize the classification.

4. Conclusions

(1) The RSM needs validation to be suitable for flow field simulation of FFCH.
(2) The tangential velocity is similar to the flow field of the conventional hydrocyclone. There is longitudinal vortex in the axial direction. The radial velocity is very small outside the entrance and the bottom area, which is not conducive to the particle classification.
(3) It can be seen from the particle concentration that it is zero in the central area; the particles are clustered near the wall and the bottom that does not achieve the purpose of the classification well.
(4) Improvement of the classification efficiency can be achieved by increasing the density of liquid, reducing the inlet velocity, increasing FFCH diameter, changing the structure size and position of FFCH outlet, adding the auxiliary parts.

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