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Research on the Inner Water Flow Field in a Hydrocyclone by the Method of 3D Numerical Simulation

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Abstract: The inner water flow field in a hydrocyclone was simulated by the software of computational fluid dynamics-FLUENT, using RSM turbulent model. The air core, 3D velocity field distribution and pressure field distribution were simulated and contrasted with experimental results. The results indicated that the air core was through from the inlet to the outlet. The simulated 3D velocity field distribution was consistent with the results obtained by the experiments. The axial symmetry of pressure field distribution was quite good and the pressure gradient was very large. All these results tested the reliability of the method of numerical simulation and provided a reference for the further research of solid-liquid separation and the optimizing design of the hydrocyclone.

Key words: FLUENT, numerical simulation, air core, velocity field, pressure field

INTRODUCTION

The hydrocyclone is a simple device that uses the centrifugal force for separation of materials in a fluid-particle stream. Although, early in 1891 hydrocyclone had come out, its related research and applications were mostly involved in grading and the application in solid-liquid separation area was relatively small. Unlike the gravity separation equipment, the hydrocyclone utilizes less space and is easy to install and control. So, more and more attention is paid to the application in the solid-liquid separation field. The hydrocyclone utilizes the energy obtained from fluid pressure to creat rotational fluid motion.

Although, the hydrocyclone has a simple structure, there are internal and external rotational flow, circular flow and short circuit flow and the air core inside the hydrocyclone. So, the inner flow rule is very complicated. (Fisher and Flack, 2002) From the view of research method, usually the water flow field is firstly studied and then the solid-liquid separation is further studied.

From the 1950s, the research on the hydrocyclone is mostly carried by the experiment. However, the research will cost a long period and a high expense only by the method of experiment.

So, as the base of further studying the solid-liquid separation, the inner water flow field in a hydrocyclone was simulated and the flow details were studied roundly by the method of Computational Fluid Dynamics (CFD), using the software, FLUENT.

GEOMETRIC MODEL

The geometric model for numerical simulation is shown in Fig. 1.

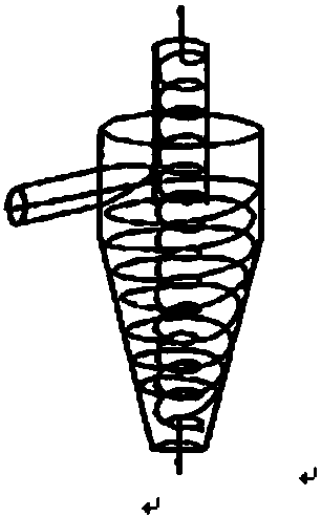

Fig. 1: Geometrical model of hydrocyclone

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MATHEMATICAL MODEL

Basic equations: Without regard to the thermal effects due to the friction between the wall and the fluid, The time-averaged equations for steady, isothermal, incompressible turbulent flows can be written in Cartesian tensor notation as (Lu *et al*., 2000):

Continuity equation:

$$\frac{\partial u_i}{\partial x_j} = 0 \tag{1}$$

Navier-Stokes equation:

$$\frac{\partial}{\partial t}(\rho u_1) + \frac{\partial}{\partial x_j}(\rho u_1 u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_i}\right) - \rho\overline{u'_i u'_j}\right] \tag{2}$$

where, $x_1 = (x_1, x_2, x_3)$ represents the Cartesian coordinates, $u_i = (u_1, u_2, u_3)$ is the mean velocity component, p is the pressure, μ is the molecular viscosity and ρ is the density:

$$\rho\overline{u_i' u_j'}$$

represents the six components of Reynolds stresses, which should be determined by the turbulence model.

Turbulence model: The hydrocyclone using for practical engineering generally works in the turbulent area. Turbulence models commonly used in engineering are standard k-ε model, RNG k-ε model and Reynolds Stress Model (RSM). The former two did not break through the isotropic framework (Liu *et al*., 2005), while hydrocyclone is based on the strong anisotropic three-dimensional swirl, so this study utilized the Reynolds Stress Model (RSM).

In RSM, the exact equations used for the Reynolds stress components can be written in Cartesian tensor notation as (Zhang *et al*., 2005).

(Hu *et al*., 2005):

$$\frac{\partial}{\partial t}(\rho\overline{u_i' u_j'}) + \frac{\partial}{\partial x_k}(\rho u_k \overline{u_i' u_j'}) = D_{i,j} + p_{i,j} + G_{i,j} + \Phi_{i,j} - \varepsilon_{i,j} + F_{i,j} + S_{user} \tag{3}$$

where:

$$D_{ij} = -\frac{\partial}{\partial x_k}[\rho\overline{u_i' u_j' u_k'} + \overline{p(\delta_{kj}u_i' + \delta_{ik}u_j')} - \mu\frac{\partial}{\partial x_k}(\overline{u_i' u_j'})] \tag{4}$$

$$p_{i,j} = -\rho(\overline{u_i' u_k'}\frac{\partial u_j}{\partial x_k} + \overline{u_j' u_k'}\frac{\partial u_i}{\partial u_k}) \tag{5}$$

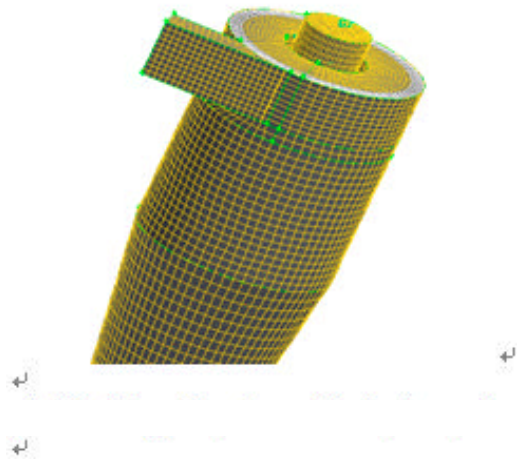

Fig. 2: 3D grid system of the hydrocyclone

$$G_{i,j} = -\rho\beta(g_i\overline{u_j'\vartheta} + g_j\overline{u_i'\theta}) \tag{6}$$

$$\Phi_{i,j} = \overline{p(\frac{\partial u_i'}{\partial x_j} + \frac{\partial u_j'}{\partial x_i})} \tag{7}$$

$$\varepsilon_{i,j} = 2\mu\overline{\frac{\partial u_i'}{\partial x_k}\frac{\partial u_j'}{\partial x_k}} \tag{8}$$

$$F_{i,j} = -2\rho\Omega_k(\overline{u_j' u_m'}\varepsilon_{ikm} + \overline{u_i' u_m'}\varepsilon_{jkm}) \tag{9}$$

S_{user} is defined by the user.

GRID SYSTEM

The actual computation was carried out in a irregular three-dimensional area. To fit the boundary shape and boundary conditions more precisely, the grid lines need to be orthogonal with the boundary lines of the physical region. Near the cylinder wall and the center area, the grid is dense and far away from the cylinder wall, the grid is sparse. Fine nodes are arranged near the wall and coarse grid nodes are arranged in other regions. Near the core greater velocity gradient appears. In order to better capture the actual flow characteristic in the boundary, the boundary layer mesh is divided on the cross section. Finally, the whole grid system is generated by the software GAMBIT, Shown in Fig. 2.

RESULTS AND DISCUSSION

Air core: In the hydrocyclone, the general velocity of three-dimensional motion increases with the reduction of the radius and the axial core in the hydrocyclone is a negative pressure zone. Because of the underflow pipe's

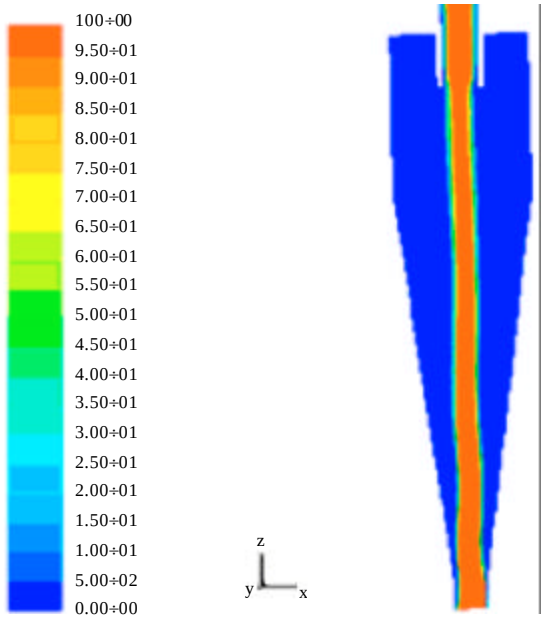

Fig. 3: Air volume fraction distribution contour

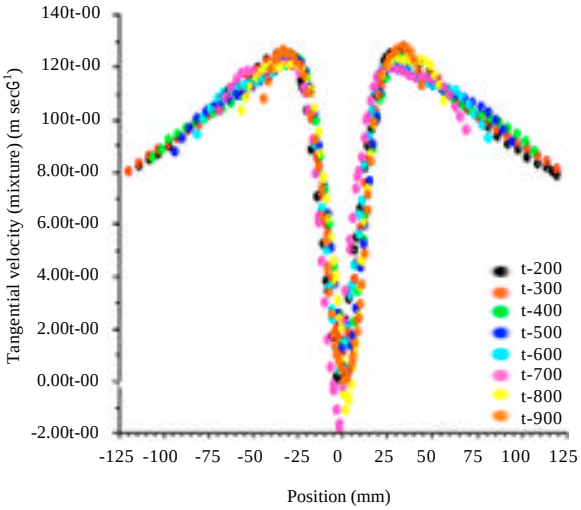

Fig. 4: Tangential velocity distribution on every cross- section

open to atmosphere, the negative pressure area absorbs the outside air, which will forms the air core. Formation of the air core in the hydrocyclone is considered to be an indication of vortex stability. It is essential to maintain the feed rate and the pressure is sufficient to operate in stable operating range. It indicates that the necessary condition forming the air column is that the inlet pressure must reach a certain minimum value. The simulation began with the water field and the air phase was added after a stable water flow field was obtained. operation. The size and stability of the air core is believed to affect the

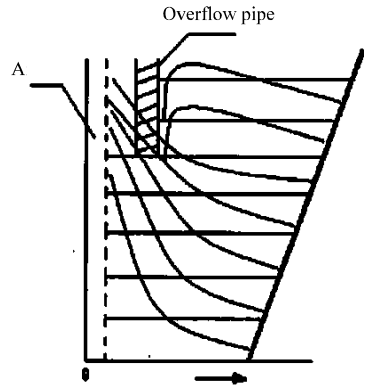

Fig. 5: Practical tangential velocity distribution measured by experiments

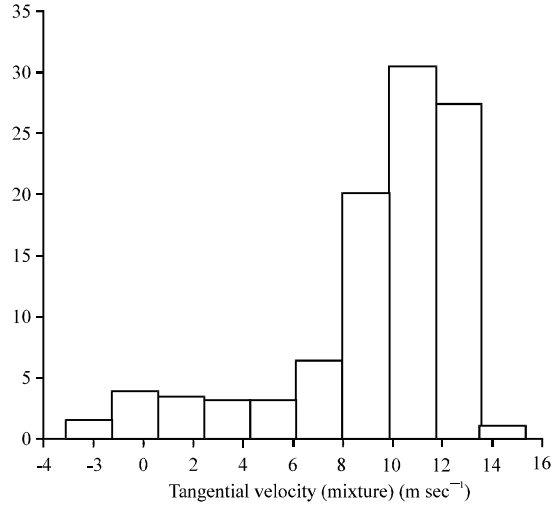

Fig. 6: Histogram of the tangential velocity

metallurgical performance of the separator (Mousavian and Najafi 2009) The final shape and volume fraction of the air core were showen in Fig. 3 clearly. The air core was through from the inlet to the outlet, which is consistent with the actual condition.

Velocity distribution of the flow field: The velocity of the flow in the hydrocyclone consists of tangential velocity, axial velocity and radical velocity. Tangential velocity is numerically larger than the other two directional velocities and has a leading position. The distribution of tangential velocity was given by the method of numerical simulation, as shown in Fig. 4, 5 shows the experimental result (Liu *et al*., 2005). Predictions are in good agreement with experimental measurements. The distribution curve of tangential velocity takes on the symmetrical "hump" shape, which is helpful to increase the centrifugal force and to improve the separation performance of the hydrocyclone. Figure 6 shows the histogram of the

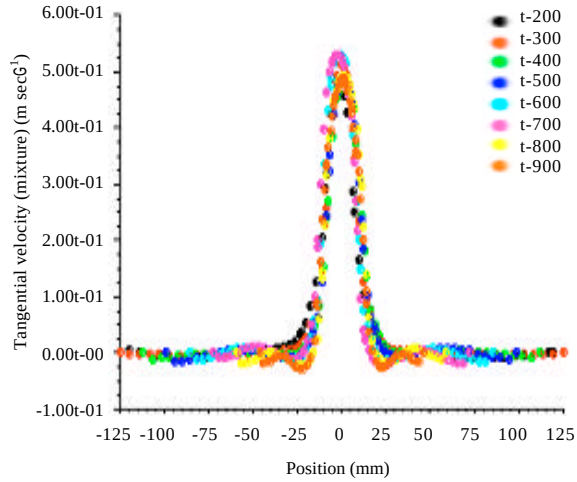

Fig. 7: Axial velocity distribution on every cross-section

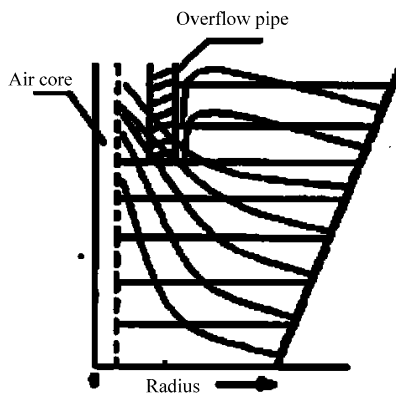

Fig. 8: Practical axial velocity distribution measured by experiments

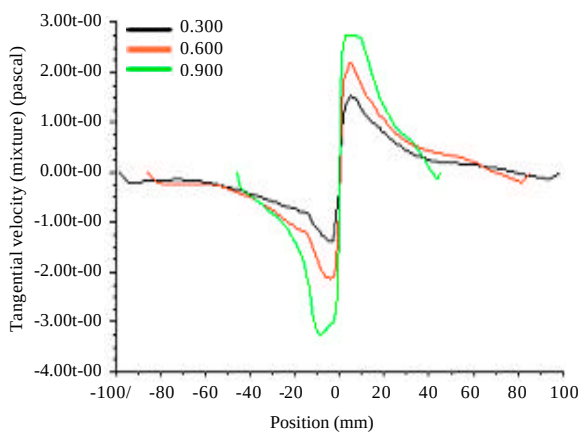

Fig. 9: Radial velocity distribution on every cross-section

tangential velocity. We can see that most of the tangential velocity is positive, which is due to the main rotational direction's consistency with the right-hand rule. But because of the existence of local secondary vortex, a minimal part of the tangential velocity of the fluid is negative, which indicated that its direction of rotation is inconsistent with the mainstream.

The axial velocity distribution on every cross-section is shown in Fig. 7. Predictions are in good agreement with experimental measurements shown in Fig. 8. In the three-dimensional flow of the hydrocyclone, the axial velocity changed significantly. Although the axial velocity of the liquid flow and its distribution have no direct effect on the position of the solid particles in the radial direction, it does determine the allocation of the fluid medium in the overflow and the bottom stream. The axial velocity distribution along the radial axis has a good symmetry and can be divided into upstream and downstream. The interface of between the upstream and downstream is called zero axial speed envelope surface (LZVV). The axial velocity gradient is very big in the central area of the air core.

In the flow three-dimensional movement in the hydrocyclone, the radial velocity is the most difficult to study and to test by the experiments. Even if the modern laser velocimetry technology is used to test the radial velocity, it's also a difficult job. The simulation result of the radical velocity is shown in Fig. 8. As shown in Fig. 9, the radical velocity has a large velocity gradient and changes sharply near the center of the hydrocyclone.

Pressure distribution of the inner flow field: Hydrocyclone is essentially a device that translates pressure energy into kinetic energy, so the pressure drop is an important reflection of the hydrocyclone's energy loss. From Fig. 10 we can see the total pressure distribution on every cross-section. The distribution

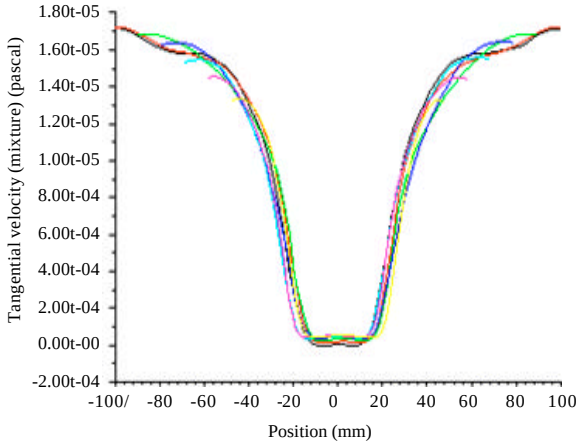

Fig. 10: Total pressure distribution on every cross-section

curve takes on a better axial symmetry and the pressure is lowest in the area of air core, which is the reason of forming air core. Near the air core, the pressure gradient is large which will generate a larger energy loss. Inside the air core, the pressure has little change.

CONCLUSIONS

Air core is formed because of the negative pressure in the center of the hydrocyclone and the air core is through from the inlet to the outlet.

Predictions from simulated 3D velocity field distribution were consistent with the results obtained by the experiments.

The total pressure distribution curve takes on a better axial symmetry and has a larger pressure gradient near the air core.

All these results tested the reliability of the method of numerical simulation and provided a reference for the further research of solid-liquid separation and the optimizing design of the hydrocyclone.

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