CFD numerical simulation of Archimedes spiral inlet hydrocyclone

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Abstract: For traditional linear type inlet, hydrocyclone has an unstable inner field, high turbulence intensity and low separation efficiency, this paper proposes an inlet mode that uses an Archimedes spiral hydrocyclone. A Mixture liquid-solid multiphase flow model combined with the kinetic theory of granular flow was used to simulate the high concentration water-sand-air three-phase flow in a hydrocyclone. We analyzed the pressure field, velocity field and turbulent kinetic energy and compared with traditional linear type inlet hydrocyclone inner field. The results show that Archimedes spiral inlet hydrocyclone’s pressure field is evenly distributed. The Archimedes spiral inlet hydrocyclone can guide and accelerate the mixture flow and produce small forced vortex and less short circuit flow. The particles easily go to the outer vortex and are separated. The Archimedes spiral inlet hydrocyclone has effectively improved the stability of inner flow field and separation efficiency.

1. Introduction
The working principle of hydrocyclone is centrifugal separation theory. It can separate several immiscible mediums. For its simple structure and maintenance, small footprint and no movable parts, hydrocyclone has widely used in petrochemical engineering, mining and agriculture water-saving irrigation[1].

The traditional hydrocyclone inlet is linear type. The linear inlet structure is simple and easy to manufacture. While it also has many problems, the traditional linear inlet hydrocyclone’s separation efficiency is low, the inner flow field is instability and energy loss is serious. So design a reasonable structure can improve working efficiency and save energy.

The inlet of hydrocyclone is the focus of many scholars. L Y Chu, W M Chen[2] researched involute-rectangle inlet, tangent-circle inlet and arcs-retangle inlet. The result shows that tangent-circle inlet has the highest separation efficiency. The efficiency is 20% higher than the other
inlets. B A Will [3] proposed that rectangle inlet is better for mixture to expand than circle inlet. Reducing section linear type inlet can transform some pressure energy to kinetic energy by the compression flow. F Li, C Y Liu, M H Jiang et al[4] designed an Archimedes spiral inlet hydrocyclone and pointed out it has advantage in leading mixture, steady flow field, and reduced abrasion. But the result hasn’t been confirmed. This paper first used CFD method to simulate the Archimedes spiral inlet hydrocyclone and analyzed the inner flow field. The simulation results compared with traditional linear type inlet hydrocyclone. This paper can provide reference to improve the hydrocyclone inlet.

2. Mathematic model
The Mixture liquid-solid multiphase flow mode is a complicated method to simulate multiphase. It solves flow, particle continuity equation and momentum equation respectively.

2.1. Control equation of water phase

2.1.1. Continuity equation of water phase

\[
\frac{\partial}{\partial t}(\bar{\alpha}_c \rho_c) + \frac{\partial}{\partial x_j}(\bar{\alpha}_c \rho_c u_{cj}) = 0
\]  

(1)

2.1.2. Momentum equation of water phase

\[
\frac{\partial}{\partial t}\left(\bar{\alpha}_c \rho_c u_{ci}\right) + \frac{\partial}{\partial x_j}\left(\bar{\alpha}_c \rho_c u_{cj}u_{cj}\right) = \left(-\bar{\alpha}_c \frac{\partial p_c}{\partial x_j}\right) + \bar{\alpha}_c \rho_c g_i - \frac{\partial}{\partial x_j}\left(\bar{\alpha}_c \rho_c u_{cj}u_{cj}\right)
\]  

(2)

\(\bar{\alpha}_c\) is the average volume fraction of water, \(\rho_c\) is density of water, \(u_{ci}, u_{cj}\) are respective average velocities in i, j direction, \(p_c\) is the pressure of water, \(\tau_{cj}\) is the viscous stress of water, \(u'_{ci}, u'_{cj}\) is the pulsation velocity of water, is the acceleration of gravity in i direction, \(\bar{\alpha}_c \rho_c u_{ci}u_{cj}\) is the Reynolds stress of water.

2.2. Control equation of particle

2.2.1. Continuity equation of particle phase

\[
\frac{\partial}{\partial t}(\bar{\alpha}_p) + \frac{\partial}{\partial x_j}(\bar{\alpha}_p u_{pi}) = 0
\]  

(3)

2.2.2. Momentum equation of particle phase

\[
\frac{\partial}{\partial t}(\bar{\alpha}_p \rho_p u_{pi}) + \frac{\partial}{\partial x_j}(\bar{\alpha}_p \rho_p u_{pj}u_{pj}) = (-\bar{\alpha}_p \frac{\partial P_p}{\partial x_j}) + \bar{\alpha}_p \rho_p g_i - \frac{\partial}{\partial x_j}(\bar{\alpha}_p \rho_p u_{pj}u_{pj})
\]  

(4)

\(\bar{\alpha}_p\) is the average volume fraction of particle. For the anisotropic turbulence in hydrocyclone, the mixed Reynolds stress \(u'_{pi}u'_{pi}\), the turbulent kinetic equation of \(k_m\) and the turbulent dissipation equation of \(\varepsilon_m\) should be established. The turbulent kinetic equation and the dissipation equation are given as

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} \left(\rho k u_{ji}\right) = \frac{\partial}{\partial x_j} \left[\mu + \frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x_j}\right] + \frac{1}{2} (P_p + G_p) - \rho \varepsilon
\]  

(5)
\[
\frac{\partial \rho \xi}{\partial t} + \frac{\partial}{\partial x} (\rho u_i) = \frac{\partial}{\partial x} \left[ \left( \mu + \frac{\mu_s}{\sigma_s} \right) \frac{\partial \varepsilon}{\partial x} \right] + C_i \frac{1}{2} \left( P_i + C_{i3} G_{ij} \right) \frac{\varepsilon}{k} - C_{i2} \frac{\rho \varepsilon^2}{k} \tag{6}
\]

where \( C_\mu = 0.09, \sigma_s = 0.82, \sigma_x = 1.0, C_{i1} = 1.44, \ C_{i2} = 1.92, \ C_{i3} \) is a function associated to gravity. 

3. Archimedes spiral inlet hydrocyclone numerical simulation

3.1. Archimedes spiral inlet hydrocyclone model establish

Archimedes spiral is a common curve in mechanical design. It is also called curve of equal velocity. The equation of Archimedes spiral is

\[
\rho = \frac{R \theta}{360} \tag{7}
\]
\[
\theta = 720 t \tag{8}
\]

The key to establish Archimedes spiral inlet hydrocyclone is to ensure the Archimedes spiral tangent to hydrocyclone cylinder. As shown in Fig.1, curve 1 is Archimedes spiral, curve 2 is the auxiliary circular arc, curve 3 is the profile of hydrocyclone cylinder. Curve 3 intersects curve 2 at B. The position of B decides the effective width W and sectional area of inlet. The sectional area is an important parameter which can affect the value of initial angular momentum. This paper researched the 100mm hydrocyclone. So brought \( R = 50 \) to Eq. (7), curve 1 was achieved. The curve 1 intersected X negative axis at A. Drew a line through A perpendicular to curve 1 and ensured AO’ = 50mm. O’ is the center of hydrocyclone cylinder. According to effective width to confirm the position of B, drew an arc through B[4]. The Archimedes spiral inlet was achieved.

![Figure 1. Diagram of Archimedes spiral inlet.](image)

3.2. Mesh generation

According to above method to establish Archimedes spiral inlet hydrocyclone model with Pro/e, the overflow pipe diameter is 25mm, the underflow pipe is 20mm and the cone angle is 15°. The height of cylinder is 150mm. Inputted the model to meshing software Gambit and used split structure meshes.
technology to mesh the model. Checked the meshes and ensured the skew rate less than 0.97\textsuperscript{[6-7]}. The final meshes were 156443. The meshing sketch is shown in Fig. 2.

![Meshing sketch of hydrocyclone model](image)

**Figure 2.** Meshing sketch of hydrocyclone model

3.3. Boundary conditions and solving parameters
The inlet and overflow pipe can consider as fully development. Inlet was set as velocity inlet. The speed of water and sand is 5m/s. The turbulent intensity is 5%. The diameter of particle is from 5 to 10\textmu m. The density of sand is 2500kg/m\textsuperscript{3}. The volume fraction is 5%. The overflow and underflow were set as pressure outlet. In order to consider the air core, the overflow and outflow contacted with the atmosphere. The relative pressure of overflow and underflow set as 0. The backflow volume fraction of water and sand set as 0. The backflow volume fraction of air set as 1. The most accurate turbulent model RSM (Reynolds Stress equation Model) was selected to simulate. All the walls were stationary. SIMPLEC algorithm and QUICK discrete scheme were selected to improve calculation accuracy\textsuperscript{[8-9]}.

4. Simulation results and analysis
The pressure contours across a vertical section through the center of Archimedes spiral inlet hydrocyclone is presented in Fig. 3(a). The pressure contours across a vertical section through the center of traditional linear type inlet hydrocyclone is presented in Fig. 3(b). The change trend of the two pressure field is the same. The pressure is high near the wall and gradual reducing with the radius decrease. The pressure value is negative in the center shows the air core appears. The Archimedes spiral inlet hydrocyclone pressure distribution is evener than the traditional linear type inlet hydrocyclone and the stability is better.

The velocity contours across a vertical section through the center of Archimedes spiral inlet hydrocyclone is presented in Fig. 4(a). The velocity contours across a vertical section through the center of traditional linear type inlet hydrocyclone is presented in Fig. 4(b). As shown in Fig. 4, the maximum velocity of two kind hydrocyclones all emerges in the inlet. The Archimedes spiral inlet...
The initial velocity of two kind hydrocyclones is 5m/s. It indicates that Archimedes spiral inlet hydrocyclone can guide and accelerate the input mixture flow. In the center of axis, the forced vortex is shown. The Archimedes spiral inlet hydrocyclone’s forced vortex is smaller than the traditional linear inlet hydrocyclone. So the flow field is more stable too.

**Figure 3.** The (a) pressure contours across a vertical section through the center of Archimedes spiral inlet hydrocyclone, and the (b) pressure contours across a vertical section through the center of traditional linear type inlet hydrocyclone.

**Figure 4.** The (a) velocity contours across a vertical section through the center of Archimedes spiral inlet hydrocyclone, and the (b) velocity contours across a vertical section through the center of traditional linear type inlet hydrocyclone.

The turbulent kinetic energy contours across a horizontal section through the Archimedes spiral inlet hydrocyclone is presented in Fig. 5(a). The turbulent kinetic energy contours across a horizontal section through the traditional linear inlet hydrocyclone is presented in Fig. 5(b). Turbulence would bring intense disturbance and pulsation to hydrocyclone inner flow field. So, high turbulent kinetic energy can decrease the stability of flow field and separation efficiency. As shown in Fig.5, the Archimedes spiral inlet hydrocyclone turbulent kinetic energy value is smaller than the traditional linear hydrocyclone. So the flow field is more stable.

**Figure 5(a).** The turbulent kinetic energy contours across a horizontal section through the Archimedes spiral inlet hydrocyclone.

**Figure 5(b).** The turbulent kinetic energy contours across a horizontal section through the traditional linear inlet hydrocyclone.
The tracking of particles inside the Archimedes spiral inlet hydrocyclone is depicted in Fig. 6(a). The tracking of particles inside the traditional linear inlet hydrocyclone is depicted in Fig. 6(b). As shown in Fig. 6(a), most particles go to outer vortex and go out from underflow pipe without difficulty. These particles are separated effectively. While in Fig. 6(b), many particles are in cyclical motion at the cylinder. Some particles go to short circuit flow and go out from overflow pipe directly. These particles are not separated. It indicates that the Archimedes spiral inlet hydrocyclone is good at particles going to outer vortex and be separated. The short circuit flow is less than traditional linear inlet hydrocyclone too. Separation efficiency of two kind hydrocyclone is shown in Fig. 7. The Archimedes spiral inlet hydrocyclone’s separation efficiency is higher than the traditional linear inlet hydrocyclone’s.

![Figure 6. The (a) tracking of particles inside the Archimedes spiral inlet hydrocyclone, and the (b) tracking of particles inside the traditional linear inlet hydrocyclone.](image)

![Figure 7. Separation efficiency of the Archimedes spiral inlet hydrocyclone and the traditional linear inlet hydrocyclone.](image)

5. Conclusions
Mixture liquid-solid multiphase flow model combined with the kinetic theory of granular flow can simulate the Archimedes spiral inlet hydrocyclone inner field and compared with the traditional linear inlet hydrocyclone inner field. The conclusions are as follows:

1. The Archimedes spiral inlet hydrocyclone’s pressure field is evener than traditional linear inlet hydrocyclone. The Archimedes spiral inlet hydrocyclone can guide and accelerate the input mixture flow and produce small forded vortex. The value of turbulent kinetic energy is smaller than the traditional linear input hydrocyclone. So the Archimedes spiral inlet hydrocyclone’s inner field is more stability than the traditional linear inlet hydrocyclone.

2. The particles are easy to go to outer vortex and separated with the Archimedes spiral inlet hydrocyclone. The short circuit in Archimedes spiral inlet hydrocyclone is less than traditional linear input hydrocyclone. The Archimedes spiral inlet hydrocyclone has effectively improved stability of
inner flow field and separation efficiency.

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