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Effect of Structure on Oil-Water Separation Performance of Cylindrical Hydrocyclone

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Abstract:

As a new type of oil-water cyclone separation, cylindrical cyclone oil-water separator has many factors affecting its performance. In this paper, the influence of inlet structure is studied by numerical simulation. The results show that the diversion effect of different port structures is different, which affects the flow field distribution in the hydrocyclone. Among them, the effect of rectangular spiral inlet diversion is the best. At the same flow area, the separation efficiency of spiral hydrocyclone is the highest, and the separation efficiency of circle is slightly higher than that of rectangle. The numerical simulation shows that the upper position of the inlet is conducive to oil-water separation

Keywords*: Cylindrical Hydrocyclone, Numerical simulation, Inlet structure, Separation efficiency, Flow field.*

I. INTRODUCTION

Hydrocyclone was widely used in chemical industry [1], mineral processing [2], metallurgy [3], coal [4] and other industries 100 years ago. It uses tangential inlet to convert the linear motion of incoming flow into rotary motion, so as to form a swirl field [5]. In the swirl field, due to the density difference between components, the components with high density move towards the wall and downward to form an external swirl, which is finally discharged from the underflow port; The components with low density gradually move towards the center and upward to form internal swirling flow, which is finally discharged from the overflow port, so as to realize the separation of different components. However, the application of hydrocyclone to oil-water separation in petroleum industry has been in recent thirty years [6].

The structure of hydrocyclone is the key factor affecting the oil-water separation performance of hydrocyclone. Many scholars at home and abroad have studied the influence of hydrocyclone structure on oil-water separation performance, and achieved some important results. Liang Yin Chu et al. [7] studied the influence of inlet, inner overflow pipe, underflow pipe and other structures on the oil-water separation

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performance of conical hydrocyclone, and found that the pressure drop and separation efficiency are different with different structures; Gay [8] et al. Found that the separation performance of dynamic hydrocyclone is better than that of static hydrocyclone; Bednarski et al. [9] explored the influence of inlet diameter on oil-water separation of hydrocyclone, and found that small inlet diameter will cause oil drop breakage, and large inlet diameter ca not make the incoming liquid form sufficient rotation strength in the hydrocyclone; Colman D.A. et al. [10] conducted relevant experiments on large-diameter and small-diameter conical hydrocyclones, and concluded that small-diameter hydrocyclones can better separate oil and water; Ding Xuming et al. [11] compared the effects of different inlet structures on the separation performance of conical hydrocyclones and found that the inlet structure has an impact on its treatment capacity and pressure drop. The above literature research shows that there are many previous studies on the influence of structure on the oil-water separation performance of conical hydrocyclone, but there are few studies on the influence of structure on the separation performance of new cylindrical hydrocyclone. Therefore, this paper will focus on the influence of the inlet structure of cylindrical hydrocyclone on the oil-water separation performance, including the influence of different inlet position, inlet shape and inlet mode on the oil-water separation performance of cylindrical hydrocyclone.

II. NUMERICAL SIMULATION

2.1 Governing Equations for Numerical Simulation of Two-Phase Flow

This paper intends to adopt the revised RNG K-ε Model [12] and mixed multiphase flow model calculate the separation law of oil and water in the cylindrical cyclone. The relevant control equations are as follows:

Continuity equation:

$$\nabla \cdot (\rho_m \vec{v}_m) = 0 \tag{1}$$

$$\rho_m = \alpha_o \rho_o + \alpha_w \rho_w \tag{2}$$

$$\vec{v}_m = \frac{\alpha_o \rho_o \vec{v}_o + \alpha_w \rho_w \vec{v}_w}{\rho_m} \tag{3}$$

Where ρ_m is the mixing density, $\vec{v}_m$ is the mass average velocity, α_o and α_w is the volume fraction of oil phase and water phase respectively; ρ_o and ρ_w are the density of oil phase and water phase respectively.

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Momentum equation:

$$\nabla\cdot(\rho_m \vec{v}_m \vec{v}_m) = -\nabla p + \nabla\cdot[\mu_m(\nabla \vec{v}_m + \nabla \vec{v}_m^T)] + \rho_m \vec{g} + \nabla\cdot(\sum_{k=1}^{2}\alpha_k \rho_k \vec{v}_{dr,k} \vec{v}_{dr,k}) \tag{4}$$

$$\mu_m = \alpha_o \mu_o + \alpha_w \mu_w \tag{5}$$

$$\vec{v}_{dr,k} = \vec{v}_{qk} - \vec{v}_m \tag{6}$$

Where μ_m is the mixed viscosity, $\vec{v}_{dr,k}$ is the drift speed of oil phase and $\vec{v}_{qk}$ is the speed of oil phase relative to water phase. Since the algebraic slip formula is used in Fluent, the form of relative speed is as follows:

$$\vec{v}_{qk} = \tau_{qk} \vec{\alpha} \tag{7}$$

Where $\vec{\alpha}$ is the acceleration of oil phase particles and τ_{qk} is the relaxation time of particles (corrected considering the existence of other particles). According to Manninen's theory, the form of τ_{qk} is as follows:

$$\tau_{qk} = \frac{(\rho_m - \rho_k) d_k^2}{18 \mu_k f_{drag}} \tag{8}$$

$$\vec{\alpha} = \vec{g} - (\vec{v}_m \cdot \nabla \vec{v}_m) \tag{9}$$

Where d_k is the diameter of oil phase particles, and the drag function f_{drag} adopts Morsi and Alexander model:

$$f_{drag} = \frac{C_D \mathrm{Re}}{24} \tag{10}$$

$$C_D = a_1 + \frac{a_2}{\mathrm{Re}} + \frac{a_3}{\mathrm{Re}^2} \tag{11}$$

$$\mathrm{Re} = \frac{\rho_k \left| \vec{\mathbf{v}}_p - \vec{\mathbf{v}}_k \right| d_k}{\mu_k} \tag{13}$$

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Where Re is the relative Reynolds number between oil and water phases.

Transport equation of turbulent kinetic energy and dissipation rate are as follows:

$$\nabla \cdot (\rho_m \vec{v}_m k) = \nabla \cdot (\frac{\mu_{t,m}}{\sigma_k} \nabla k) - \rho_m \varepsilon + G_{k,m} \tag{14}$$

$$\nabla \cdot (\rho_m \vec{v}_m \varepsilon) = \nabla \cdot (\frac{\mu_{t,m}}{\sigma_\varepsilon} \nabla \varepsilon) + \frac{\varepsilon}{k}(C_{1\varepsilon} G_{k,m} - C_{2\varepsilon} \rho_m \varepsilon) \tag{15}$$

$$G_{k,m} = \mu_{t,m}[\nabla \vec{v}_m + (\nabla \vec{v}_m)^T] \nabla \vec{v}_m \tag{16}$$

$$\mu_{t,m} = \rho_m C_\mu \frac{k^2}{\varepsilon} \tag{17}$$

$$C_{1\varepsilon} = 1.44, \quad C_\mu = 0.0845, \quad C_{2\varepsilon} = 1.92, \quad \sigma_k = 1.0, \quad \sigma_\varepsilon = 1.3 \tag{18}$$

Where k is the turbulent kinetic energy, ε represents the dissipation rate, $G_{k,m}$ represents the turbulent kinetic energy generation phase, and $\mu_{t,m}$ represents the turbulent viscosity.

Volume fraction equation:

$$\nabla \cdot (\alpha_o \rho_o \vec{v}_m) = -\nabla \cdot (\alpha_o \rho_o \vec{v}_{dr,o}) \tag{19}$$

Boundary conditions and numerical solution:

1) Inlet conditions: flow pattern of homogeneous flow, inlet velocity, volume fraction of given oil phase, particle size of oil droplets.

2) Export conditions: fully developed boundary conditions.

3) Solid wall boundary condition: no slip solid wall condition.

Based on the control volume, the numerical solution converts the control equation into an algebraic equation that can be solved by numerical method. The first-order upwind difference scheme is used for the discretization of the equation, and the SIMPLE algorithm is used for the solution of the algebraic equation.

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2.1 Model Validation

In order to verify the above model, an experimental system was established in the Key Laboratory of applied multiphase flow, Institute of Mechanics, Chinese Academy of Sciences, and relevant experimental results were obtained. The cylindrical cyclone used in the experiment is made of transparent plexiglass, and its structural design size is shown in Figure 1 below.

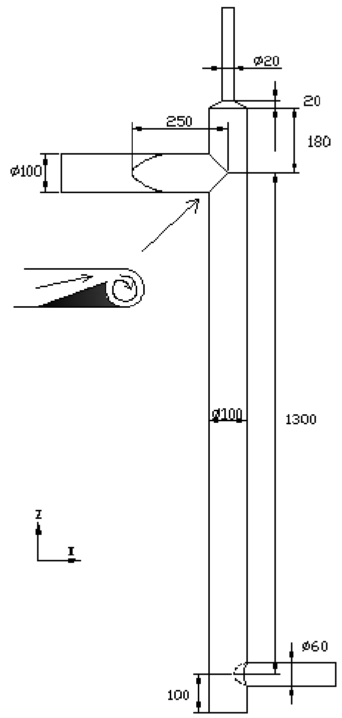

Fig 1: Structural diagram of cylindrical cyclone

In the experiment, the density of aqueous phase is 998.2 kg/m^3 and the viscosity is 1.003 × 10^{-3} Pas; The dispersed phase is lp-14 White Oil, with a density of 836.0 kg/m^3 and a viscosity of 31.0 × 10^{-3} Pas, the experimental system is as follows [13] The specific experimental process is described in the same document [13].

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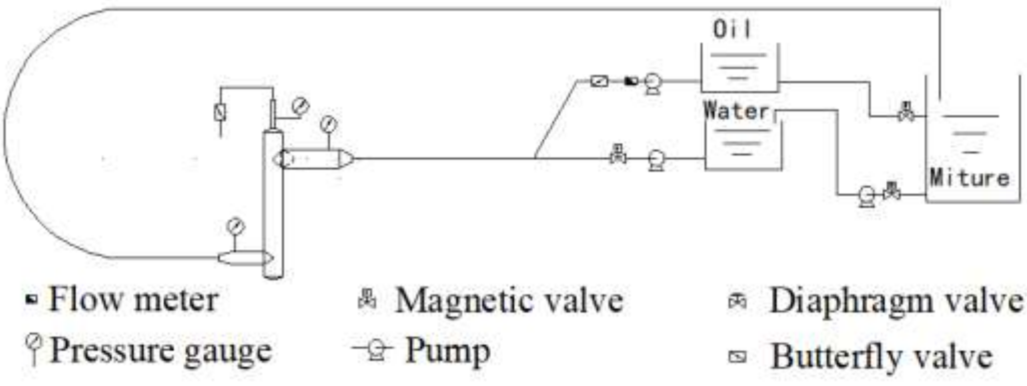


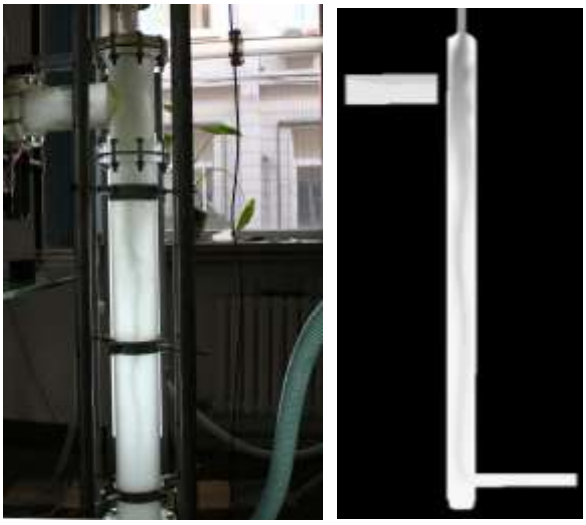
Fig 2: Schematic diagram of experimental system

The separation efficiency ε involved in the experiment is defined as the ratio of the oil content of the oil phase at the overflow port to the oil content at the inlet. The split ratio F refers to the ratio of the volume flow at the overflow port to the volume flow at the inlet, and its expression is as follows:

$$\varepsilon = \frac{k_o}{k_i} \tag{20}$$

$$F = \frac{Q_O}{Q} \tag{21}$$

Q. Q_o is the volume flow at the inlet and overflow respectively, and k_i and k_o are the oil phase volume fraction at the inlet and overflow respectively.



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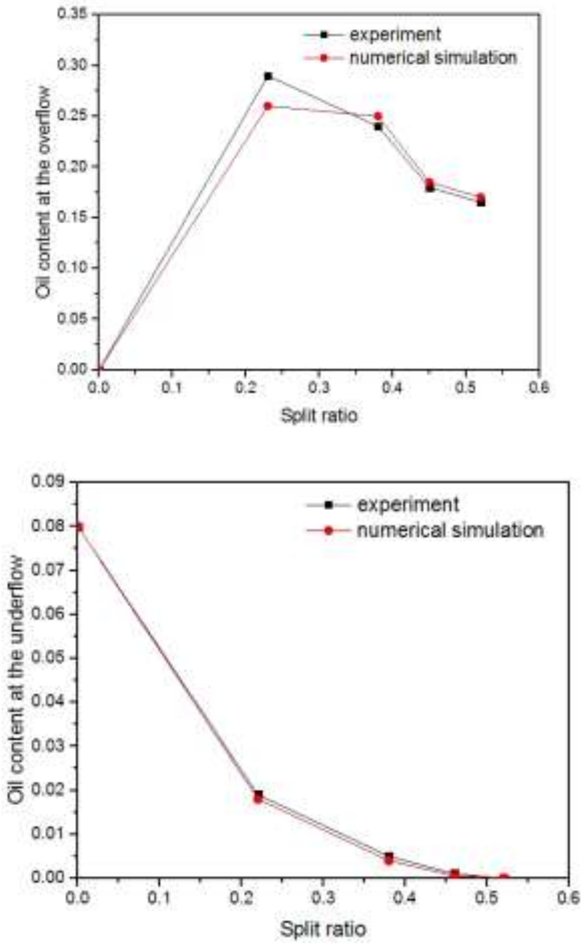

Fig 3: Comparison of experimental and numerical results

When the apparent velocity of water phase is 0.354m/s, the apparent velocity of oil phase is 0.032m/s, and the oil phase holdup at the inlet is 0.081, Fig. 3 shows the results of numerical simulation compared with the experimental situation (the gray one is oil phase). It is found that the distribution of oil-water two phases in the cylindrical cyclone is basically the same, and the error of the oil content results at the two outlets is less than 5%. The model selected in the text is basically feasible to calculate the separation of oil-water two-phase in cylindrical hydrocyclone.

2.3 Geometric Model

In order to study the influence of different inlet structure on oil-water separation in cylindrical cyclone, the inlet shape and inlet are changed respectively. Different numerical simulation experiments were carried out for the form and inlet position (as shown in Figure 4). The structure diagram, name and code of the entrance are shown in Figure 4 and TABLE I. According to the inlet shape, a and D are circular channels, and B, C, e and F are rectangular channels. During numerical simulation, ensure that the equivalent area of these channels is equal. The diameter of circular channel is 15 mm, the length and width of rectangular channel are 42.1 mm and 16.8 mm, and the long side is parallel to the axis of the column. According to the

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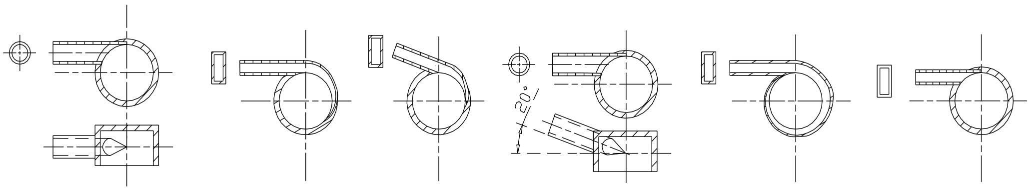
intersection form of inlet pipe and column, a and F are tangent type; B is spiral type; C is involute type; D is tangent type + the axial line of inlet pipe forms an included angle of 20 ° with the horizontal plane; E is tangent type + the spiral plate outside the inlet pipe runs around the column and intersects with the column. The height of the entrance position is taken as 4 groups: z = 500 mm, 650 mm, 800 mm and 950 mm.



A B C D E F

Fig 4: Structural design of entrance

TABLE I. Design codes and names of different entrance structures

Code	A	B	C	D	E	F
Name	Tangen t line	Spiral type	Involute type	Oblique 70 ° tangent line	Spatial spiral	Tangent line
shape	Round tube	Rectangul ar tube	Rectangul ar tube	Round tube	Rectangula r tube	Rectangul ar tube

III. ANALYSIS OF SIMULATION RESULTS

3.1 Flow Field Analysis

The vector diagram of velocity distribution on the horizontal section passing through the tangent point of the inlet and the cylinder is shown in Fig. 5. The missing vector diagram of D and E is caused by the spatial structure of the inlet (when the oil content at the inlet is 0.1, the inlet flow rate is 10 m / s, and the average particle size of oil droplets is 100 μm, the diversion ratio is 30%). It can be seen that on the premise of the same other conditions, through the guiding effect of the inlet, the minimum velocity distribution of type B and e structure is located near the center of the circle and the change of velocity direction is relatively smooth, but the velocity of type B structure at the same position is greater than that of type e structure; The change of speed direction of C-type structure is uneven, and the minimum speed deviates from the center, and the effect is the worst; A. The effects of D and F are similar, and the minimum velocities deviate from the center. The velocity distribution in the circle near the inlet of a and D is much greater than that in other areas. This distribution is easy to make the oil core swing in the cylinder, which is unfavorable. It can also be seen from the figure that the flow field after type B diversion is uniform, the average velocity is large and the energy loss is small. In conclusion, it can be seen that the diversion effect of different inlet structures is different.

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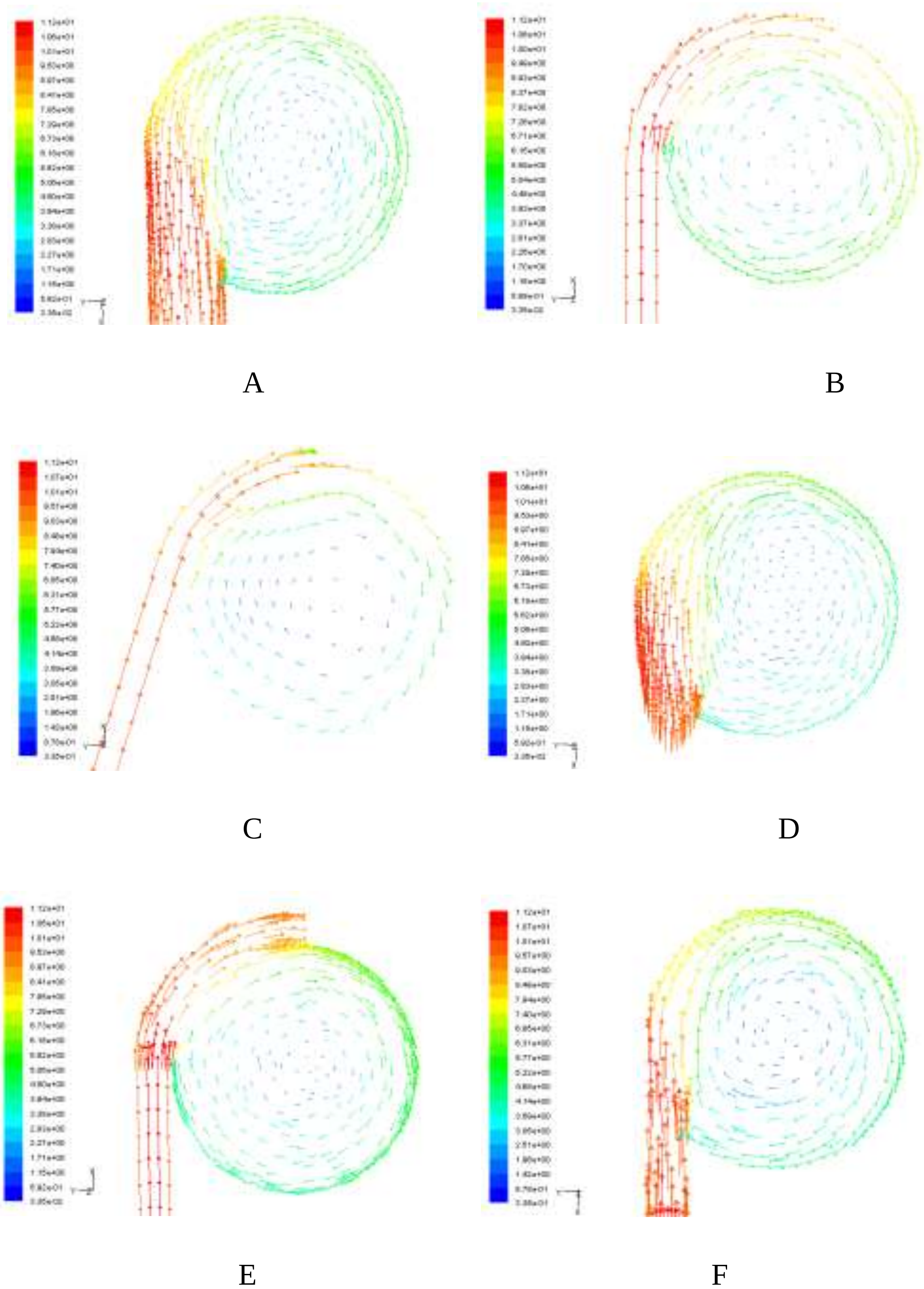

Fig 5: Velocity distribution at the inlet pipe's cross section

3.2 Effect of Inlet Shape on Oil-Water Separation Efficiency in Cylindrical Cyclone

Fig. 6 shows the comparison of separation efficiency of different inlet structures under different split ratios when the inlet oil content is 0.1, the inlet flow rate is 10m / s and the average particle size of oil droplets is 100m. It can be seen from the figure that the separation efficiency of circular inlet is slightly higher than that of rectangular inlet when ensuring that the inlet has the same flow area, the same inlet

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form, the same inlet flow rate and other working conditions; Under the condition that the inlet shape is the same and other working conditions are the same, the separation efficiency: spiral line > tangent line > involute line > three-dimensional spiral (all rectangular sections); The separation efficiency of the inlet structure (all circular sections) tangent to the cylinder is higher than that of the cylinder, which is inclined downward by 20 °. The spiral inlet structure converts the linear motion of liquid into circumferential motion, so that the incoming liquid can enter the rotating motion state more smoothly; The tangential inlet makes the incoming liquid directly enter the cylinder, which will disturb the fluid flow structure inside the cylinder and prevent the oil droplets from moving rapidly to the axis at the inlet, so its efficiency is slightly low; The reason why the separation efficiency of the three-dimensional spiral inlet structure is the lowest is that it is guided around the axis to change the tangential velocity of the inlet into the velocity tangent to the cylinder downward. The tangential velocity obtained by the decomposition of the velocity tangent to the cylinder is bound to decrease, so as to reduce the centrifugal force on the oil droplets and reduce the power of the oil droplets moving towards the center. Therefore, the separation efficiency of this structure is low. Under the same flow area and other conditions, the separation efficiency of spiral inlet structure is the highest, which is consistent with the conclusion of Yuan Yunhong et al. [14-15].

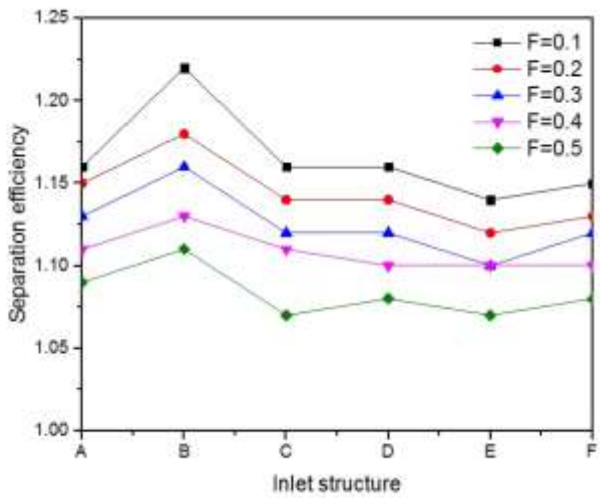

Fig 6: Comparison of separation efficiency of hydrocyclones with different inlet structures under different split ratio

3.3 Influence of Inlet Position on Oil-Water Separation in Cylindrical Cyclone

When the inlet oil content is 0.1, the inlet flow rate is 10 m / s, the split ratio is 0.2, and the average particle size of oil droplets is 100 μm, when the inlet position height Z is 50cm, 65cm, 80cm and 95cm respectively, the oil content distribution diagram of shaft section corresponding to type a hydrocyclones is shown in Figure 7. It can be seen from the figure that with the increase of the inlet position, the oil discharged from the overflow port increases, that is, the inlet position close to the overflow port is conducive to improve the separation efficiency. When the inlet position is higher, the oil in the internal cyclone can be discharged from the overflow port in time. When the inlet position is lower, the oil core

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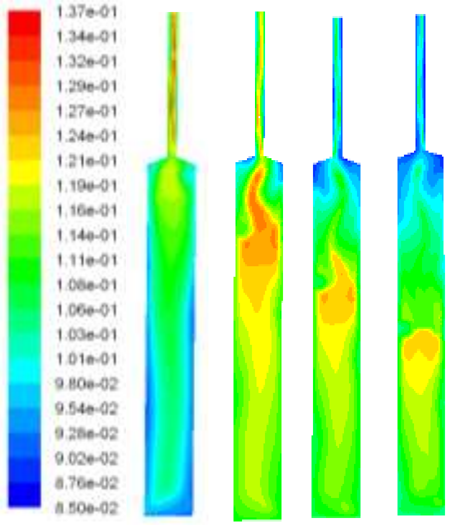
moves upward in a spiral manner because the flow field in the cyclone is asymmetric. When the inlet position is lower, the longer the spiral movement distance and the more energy loss, part of the oil droplets will dissociate from the oil core, and finally the upward moving oil core will disappear, which is particularly obvious in the third hydrocyclone in the figure below. Therefore, the upper inlet position is conducive to oil-water separation.



z= 95 80 65 50

Fig 7: Oil content distribution of cylindrical cyclone shaft section at different inlet positions

IV. CONCLUSION

The model used in the numerical simulation is verified and the results show that the error with the experiment is less than 5%. On this basis, different inlet structures and shapes are numerically calculated, and the conclusions are as follows:

(1) The diversion effect of the inlet structure is different, which affects the flow field distribution in the hydrocyclone. Among them, the rectangular spiral inlet has a large average velocity after diversion, that is, the energy loss is the smallest.

(2) When the inlet oil content is 0.1, the inlet flow rate is 10m / s, the average particle size of oil droplets is 100m, and the same flow area, the separation efficiency of spiral hydrocyclone is the highest, and the separation efficiency of circle is slightly higher than that of rectangle.

(3) When the oil content at the inlet is 0.1, the inlet flow rate is 10m / s, the split ratio is 0.2 and the average particle size of oil droplets is 100m, the numerical simulation shows that the upper position of the inlet is conducive to oil-water separation.

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