NUMERICAL AND EXPERIMENTAL STUDY ON LIQUID-SOLID FLOW IN A HYDROCYCLONE*

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Abstract: Hydrocyclones are widely used in industry, of which the geometrical design using CFD techniques is gaining more popularity in recent years. In this study, the Euler-Euler approach and the Reynolds stress model are applied to simulate the liquid-solid flowfield in a hydrocyclone. The methodology is validated by a good agreement between experimental data and numerical results. Within the research range, the simulation indicates that the liquid-solid separation mainly occurs in the conical segment, and increasing conical height or decreasing cylindrical height helps to improve the grade efficiencies of solid particles. Based on these results, two of the same hydrocyclones are designed and installed in series to establish a liquid-solid separation system. Many experiments are then conducted under different conditions, in which the effects of the water cut and the second hydrocyclone on the separation are investigated. The results also confirm that smaller solid particles are more susceptible to the inlet conditions, and the second hydrocyclone plays a more important role as the water cut reduces.

Key words: hydrocyclone, liquid-solid flow, model, efficiency

1. Introduction

Liquid-solid hydrocyclones are widely used in chemical industry and petroleum industry due to their advantages, including compact geometry, high separation efficiency and easy maintenance, etc.[1-3]. Figure 1 shows the geometry of a hydrocyclone. As can be seen, it mainly consists of inlet tube, vortex finder, cylindrical part, conical part and tail tube. After the liquid-solid mixture enters into a hydrocyclone, the denser components tend to be accumulated near the wall due to a strong swirl and spiral down to the tail tube, while a secondary vortex appears in the core region and exits from the vortex finder.

Despite its simplicity in geometry, however, the multiphase flow behaviors in a hydrocyclone are actually very complex, and lots of studies have been conducted in the past decades[4-7]. For the geometrical

design, conventionally technicians mainly use empirical or semi-empirical relationships to predict the separating performance of a hydrocyclone, or determine the main geometries under certain conditions. With the great progress in both mathematical modeling and computing power, however, computational fluid dynamics has gained more popularity in recent years[8-12]. Numerical simulation based on CFD has proven to be valuable in predicting the multiphase flow characteristics in a hydrocyclone and can reduce the costs to a large extent[13, 14]. Thus, in this study an efficient liquid-solid hydrocyclone will be primarily designed and further optimized through numerical simulations. Then, two of the same hydrocyclones are designed and installed in series to establish a liquid-solid separation system. Some experiments are performed in the first hydrocyclone to validate the simulation methodology, and then the effects of the water cut and the second hydrocyclone on the separating performances are also studied.

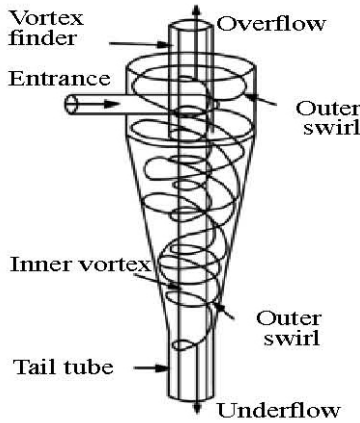* **Biography:** WANG Li-yang (1980-), Male, Ph. D.

Fig.1 Geometrical structure and its internal flowfield

2. Numerical simulation

Currently, two approaches are available to simulate the multiphase flow in a hydrocyclone, namely the Euler-Lagrange approach and the Euler-Euler one. The basic assumption in the former approach is that the volume fraction of solid is sufficiently low and its effect on the liquid phase is negligible. In industrial applications, however, the solid volume fraction is usually so high that the phasic interactions must be fully considered. The present study focuses on solid volume fraction higher than 10 percent, and therefore the Euler - Euler approach should be adopted. To be consistent with the later experiments, three kinds of solid particles, denoted by s_1, s_2 and s_3, are set in the simulation. The densities of the liquid and the solid particles are 998.0 kg/m³ and 2600.0 kg/m³, the effective spherical diameters of the solid phases are 0.149 mm, 0.210 mm and 0.297 mm respectively, while the dynamic viscosity of the liquid phase is 0.001 kg/m·s.

The commercial software "Fluent 6.1.22" is used, in which the partial differential equations describing the multiphase flow are discretized using the finite volume method. The second-order upwind scheme is applied to interpolate the variables on the surfaces of the control volume, and the pressure - velocity coupling is built through the SIMPLEC algorithm. In the computation, the iterations will not stop until the continuity residual convergence criterion of 1.0×10^{-6} is achieved.

2.1 Basic equations

Mass conservation:

$$\frac{\partial \alpha_k \rho_k}{\partial t} + \nabla \cdot (\alpha_k \rho_k \boldsymbol{v}_k) = 0 \tag{1}$$

where $k = l, s$, l is the liquid phase and s the solid phase.

Momentum conservation:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k \boldsymbol{v}_k) + \nabla \cdot (\alpha_k \rho_k \boldsymbol{v}_k \boldsymbol{v}_k) = -\alpha_k \nabla p +$$

$$\nabla \cdot \overline{\overline{\tau}}_k + \alpha_k \rho_k \boldsymbol{g} + (\boldsymbol{F}_{lift,k} + \boldsymbol{F}_{Vm,k}) +$$

$$\sum_{p=1}^{n} K_{kq}(\boldsymbol{v}_k - \boldsymbol{v}_q) \tag{2}$$

Herein, the lift force $\boldsymbol{F}_{lift}$ and the virtual force $\boldsymbol{F}_{vm}$ are calculated by

$$\boldsymbol{F}_{lift} = -0.5\rho_l \alpha_s (\boldsymbol{v}_l - \boldsymbol{v}_s) \times (\nabla \times \boldsymbol{v}_l) \tag{3}$$

$$\boldsymbol{F}_{vm} = 0.5\alpha_s \rho_l \left(\frac{d\boldsymbol{v}_s}{dt} - \frac{d\boldsymbol{v}_l}{dt}\right) \tag{4}$$

Through time scale analysis on phasic interactions in a hydrocyclone, Kraipech et al.[15] found that the particle-particle interactions only dominates near the wall and the vortex core. To reduce computational costs, therefore, only particle - fluid interactions are considered here and the exchanging coefficient is calculated with the Gidaspow model.

$$K_{sl} = 150.0 \frac{\alpha_s(1-\alpha_l)\mu_l}{\alpha_l d_s^2} + 1.75 \frac{\rho_l \alpha_s |\boldsymbol{v}_s - \boldsymbol{v}_l|}{d_s},$$

$$\alpha_l \leq 0.8 \tag{5a}$$

$$K_{sl} = 0.75 C_D \frac{\alpha_s \alpha_l \rho_l |\boldsymbol{v}_s - \boldsymbol{v}_l|}{d_s} \alpha_l^{-2.65},$$

$$\alpha_l > 0.8 \tag{5b}$$

where

$$C_D = \frac{24}{\alpha_l Re_s}\left[1 + 0.15(\alpha_l Re_s)^{0.687}\right] \tag{6}$$

Turbulence model:

An appropriate turbulence model should be applied to make the above equations close. For the strong swirling flow in a hydrocyclone, the $k - \varepsilon$ model based on eddy-viscosity approach failed to predict the multiphase flow behaviors well[16,17]. Therefore, the

Reynolds Stress Model (RSM) is selected to capture the anisotropic character of the turbulence, of which the transportation equations are as follows:

$$\frac{\partial}{\partial t}\left(\rho\overline{u_i'u_j'}\right)+\frac{\partial}{\partial x_k}\left(\rho u_k'\overline{u_i'u_j'}\right)=P_{ij}+F_{ij}+$$

$$D_{Tij}+\phi_{ij}-\varepsilon_{ij} \qquad (7)$$

$$P_{ij}=-\rho\left(\overline{u_i'u_k'}\frac{\partial u_j}{\partial x_k}+\overline{u_j'u_k'}\frac{\partial u_i}{\partial x_k}\right) \qquad (8)$$

$$F_{ij}=-2\rho\Omega_k\left(\overline{u_j'u_m'}\varepsilon_{ikm}+\overline{u_i'u_m'}\varepsilon_{jkm}\right) \qquad (9)$$

$$D_{Tij}=-\frac{\partial}{\partial x_k}\left[\rho\overline{u_i'u_j'u_k'}+\overline{p\left(\delta_{kj}u_i'+\delta_{ik}u_j'\right)}\right] \qquad (10)$$

$$\phi_{ij}=\left(\overline{\frac{\partial u_i'}{\partial x_j}+\frac{\partial u_j'}{\partial x_i}}\right) \qquad (11)$$

$$\varepsilon_{ij}=-2\mu\overline{\frac{\partial u_i'}{\partial x_k}\frac{\partial u_j'}{\partial x_k}} \qquad (12)$$

Hydrocyclone geometry:

For a liquid - solid hydrocyclone shown in Fig.2, the separating performances largely depend on its geometries, including the cylindrical diameter, the vortex finder diameter, and the tail tube diameter, etc.. As there is still a large controversy over the cylindrical height and the conical height[18], their influences on the liquid-solid separation are mainly considered in the present simulation.
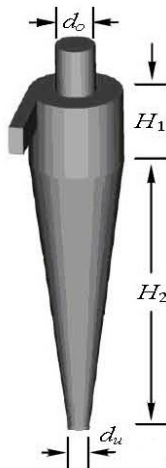
Table1 Hydrocyclone geometries in the simulation

No.	Cylindrical height $\tilde{H}_1=H_1/D$	Conical height $\tilde{H}_2=H_2/D$
C-1	0.5	2.0
C-2	0.5	3.0
C-3	0.5	4.0
C-4	1.0	3.0
C-5	1.5	3.0

The cylindrical diameter D is determined to be 150.0 mm based on the required handling capacity, while the vortex finder diameter d_o and the tail tube diameter d_u are 50.0 mm and 30.0 mm according to the Rietema optimal structure. Totally five hydrocyclones in Table 1 are considered. A number of 4×10^5-6×10^5 hexahedral cells are generated for each hydrocyclone in Gambit. To facilitate the meshing operation, the hydrocyclone geometry is split into five blocks and each block is then meshed separately. A "velocity-inlet" condition is set at the inlet, namely the normal velocities of all phases, phasic volume fractions, and the turbulence parameters are specified. Different pressures are given at the outlets of the vortex fin der and the tail tube. A no-slip condition is imposed on the internal wall, and the standard wall function is applied to deal with the turbulence adjacent to the wall region. The grid is gradually refined to ensure that the numerical results are grid-independent.
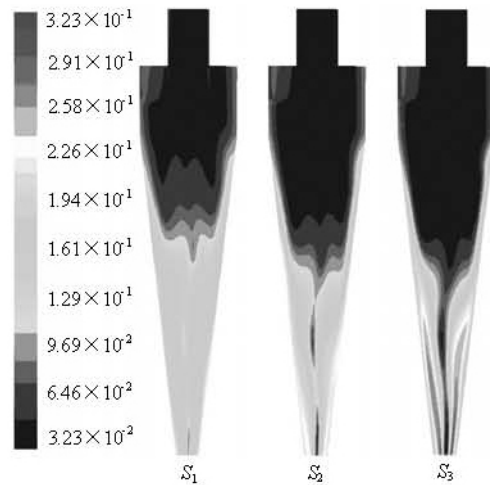

Fig.2 Geometry of hydrocyclone

Fig.3 Volume fraction contour of solid phases of C-1

2.1 Results and analyses

2.2.1 Conical height

In the simulation, the inlet velocity is 2.00 m/s, and the volume fraction of each phase s_1, s_2 and s_3 are all taken as 5.0 percent. The axial volumetric fraction contour of the solid phases in hydrocyclone C-1 is shown in Fig.3. As can be seen, the liquid-solid separation mainly occurs within the conical segment. Larger solid particles, such as phase s_3, would be separated and accumulated near the wall more quickly, while a large part of phase s_1 still exists around the core region due to the secondary vortex.

To further study the effect of conical height, hydrocyclones C-1, C-2 and C-3 are treated in the simulation. The grade efficiency, a key parameter in evaluating the separating performance[19,20], is calculated for each hydrocyclone. Figure 4 shows the calculated results. Within the research range, increasing conical height generally plays a positive role in the separation, which is consistent with the results obtained by Wang et al.[21]. It is also interesting to note that the grade efficiency of smaller solid particles can be enhanced more significantly than larger ones. In other words, elongating the conical height is especially helpful to separating small solid particles.
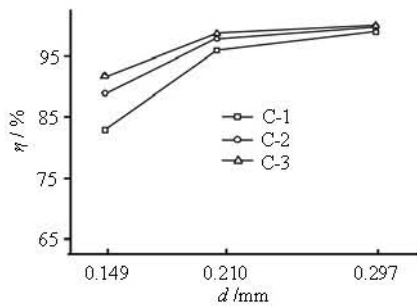

Fig.4 Grade efficiencies of C-1, C-2 and C-3

2.2.2 Cylindrical height

Chu et al.[22] considered that the separating phenomena also exist in the cylindrical part, and thus increasing the cylindrical height can improve the separating performance. In contrast, Xiang et al.[23] found a decrease of separation efficiency as the cylindrical height increases. On the other hand, Wang et al.[21] argued that the cylindrical height has a negligible effect on the separating process.

To figure out this problem, hydrocyclone C-2, C-4 and C-5 are used to investigate the influence of the cylindrical height. Both the inlet conditions and the boundary conditions are the same as those in 2.2.1. As is shown in Fig.5, the grade efficiency gradually reduces with the increase of the cylindrical height. Of the solid phases, the grade efficiency of phase s_1 decreases from 88.9 percent to 75.7 percent, much more significant than those of phase s_2 and s_3 .Therefore, the cylindrical height should be determined carefully to ensure the grade efficiency of small solid particles.
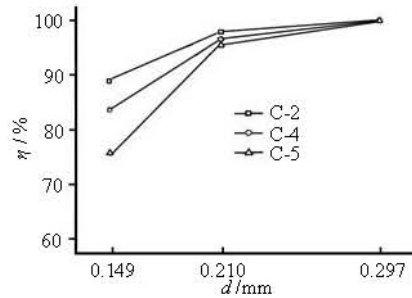

Fig.5 Grade efficiencies of C-2, C-4 and C-5

The centrifugal force, generated by the tangential velocity component of the liquid phase, plays a dominating role in the liquid-solid separating process. To further study the influences of cylindrical height, the tangential velocity of liquid phase in both axial and radial planes within hydrocyclone C-2 and C-5 are presented in Fig.6. It can be seen that the tangential velocity of the liquid phase drops with the increase of the cylindrical height, and consequently the grade efficiencies of all three solid phases are lowered.
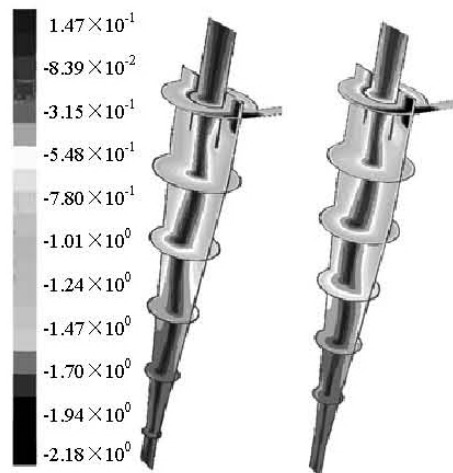

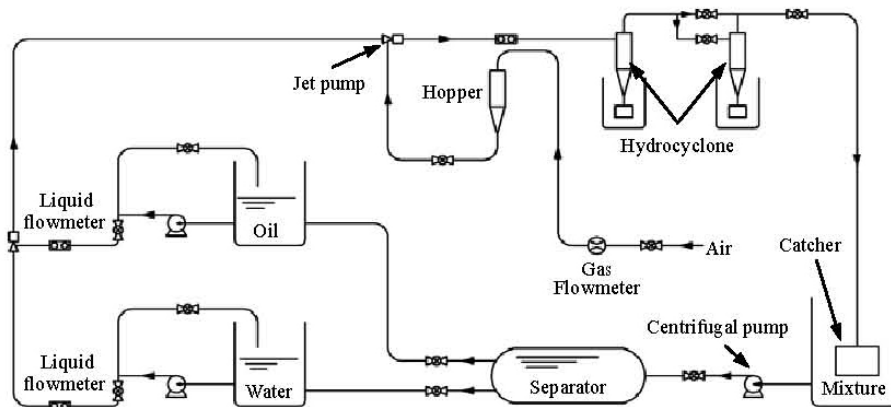Fig.6 The tangential velocity of liquid for C-2 and C-5

3. Laboratory experiments

3.1 Experimental facilities

Based on the above simulations and the practical handling capacity requirement in the laboratory,   two

(a) Photo of the liquid - solid separation system

(b) Schematic diagram of the liquid - solid separation system

Fig.7 The liquid - solid separation system

of the same hydrocyclones are designed, and their geometrical dimensions are as follows: $D = 150.0$mm , $d_o = 50.0$mm , $d_u = 30.0$mm , $H_1 = 75.0$mm , $H_2 = 525.0$mm , $H_3 = 65.0$mm . A liquid-solid separation system using the two hydrocyclones is established, for which the photo and the schematic diagram are given in Fig.7. Two valves are installed between the first and secomd hydrocyclone, and therefore the liquid - solid separation can happen in the first hydrocyclone individually or both the two hydrocyclones in series.

In the experiments, the premixed solid particles are placed in the hopper 1, and then they are introduced into the hydrocyclone 2 and 3 with oil - water mixture. Part of the solid particles are separated and collected in the settling chamber 4 and 5, and the residual particles are gathered in the catcher 6. The liquid mixture in the tank 7 is pumped into the horizontal separator 8, and then would be recycled into the oil tank 9 and the water tank 10 respectively. The inlet velocity ranges from 0 m/s to 5.00 m/s, and the physical properties of LP-14 white oil are $\rho_o = 836.0$kg / m^3 , $\mu_o = 0.031$kg / m $\cdot$ s .

3.2 *Model validation*

To validate the methodology above, some experiments are conducted in the first hydrocyclone. The averaged volume fractions of phase s_1, s_2 and s_3 are 2.7, 8.1 and 8.1 percent respectively. In the first case, solid particles are separated from water, and the inlet velocity is 1.21 m/s. In the second case, the inlet velocity is 1.83 m/s and LP-14 white oil is used as the liquid phase.
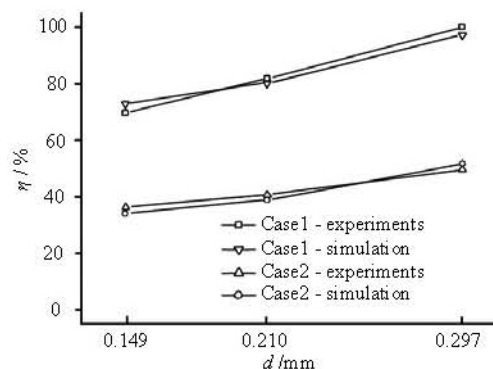

Fig.8 Experimental data and numerical results for grade efficiencies

Figure 8 compares the experimental data and the corresponding numerical results, and the largest relative error between them is no more than 4.7 percent, indicating the mathematical model above can predict the grade efficiencies of the solid particles quite well. The results also show that the liquid - solid separation depends strongly on the physical properties of the liquid phase. Despite the larger inlet velocity and the smaller density, the grade efficiencies of all solid phases are much lower in the case of the LP-14 white oil due to its higher viscosity.

3.3 Results and analyses

3.3.1 Water cut

The water cut is defined as the volume percentage of water in the oil-water mixture. The physical properties of mixture, such as the density and viscosity, would change greatly with the water cut. In the oilfields, the water cut can vary within a wide range, and the liquid-solid hydrocyclones are expected to behave well under these conditions.
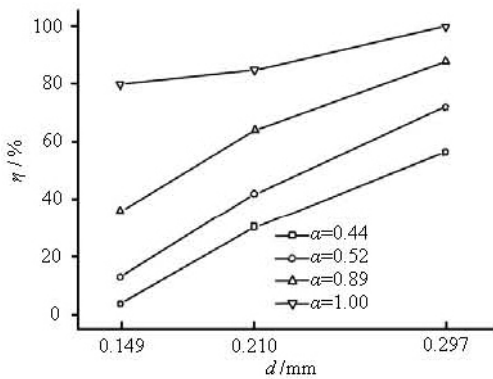
Fig.9 Grade efficiencies for phase s_1, s_2 and s_3 under different water cuts

In the experiments, the water cut ranges from 0.40 to 1.00. The inlet velocity of liquid-solid mixtures is 1.35 m/s, and the volume fraction of phase s_1, s_2 and s_3 are 3.0, 6.0 and 6.0 percent. The grade efficiencies for the phase s_1, s_2 and s_3 under different water cuts are presented in Fig.9. The grade efficiency for the phase s_1 will boost dramatically from 3.6 percent to 80.0 percent as the water cut increases, much more significant than that for phase s_3. Such result shows that smaller particles are more sensitive to the inlet conditions, which also, to some extent, confirms the simulated results above.

3.3.2 Hydrocyclone stage

As mentioned above, the separation efficiency is often improved by installing several hydrocyclones in series in the oilfields. To quantitatively describe the contributions of the second hydrocyclone to the whole liquid - solid separation under different conditions, a new parameter η_{21} is introduced herein, namely:

$$\eta_{21} = \frac{1}{1 + \dfrac{m_1}{m_2}} \tag{13}$$

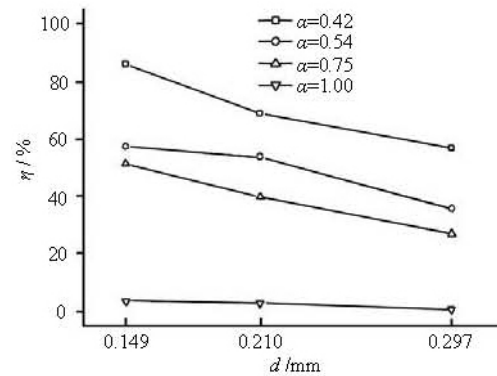where m_1 and m_2 are the mass of solid particles separated in the first and second hydrocyclones.

Fig.10 η_{21} for phase s_1, s_2 and s_3 under different water cuts

Figure 10 shows η_{21} under different water cuts. The liquid velocity is 1.50 m/s, and the volume fraction of phase s_1, s_2 and s_3 are 3.0, 3.0 and 6.0 percent respectively. In case the liquid phase is water, only a few solid particles are separated in the second hydrocyclone. However, totally about 39.4, 49.0 and 70.5 percent of solid particles are collected as the water cut reduces from 0.75 to 0.42, and the grade efficiency for the phase s_1 even arrives at 56.5, 69.0 and 85.9 percent. Therefore, the second hydrocyclone will play a dominating role in the liquid-solid separation as the water cut decreases, and installing several hydrocyclones in series is an effective way to improve the separating performances.

4. Conclusions

A kind of liquid - solid hydrocyclone has been designed and further optimized through numerical simulations integrating the Euler-Euler approach and the RSM turbulence model. Two hydrocyclones are manufactured based on the simulations and a liquid - solid separation system is established, in which lots of experiments are performed to study the effects of the water cut on the grade efficiencies, and the contributions of the second hydrocyclone to the whole separation. The following conclusions can be drawn.

(1) The simulation shows that the liquid-solid separation mainly occurs in the conical part. Within the research range, increasing the conical height can

improve the grade efficiencies for solid particles, especially those smaller ones. Besides, the grade efficiencies would gradually reduce as the cylindrical height increases. Compared to larger solid particles, the grade efficiency for smaller ones are more susceptible to the changes of the cylindrical height.

(2) The experiments confirm that the liquid - solid separation depends strongly on the physical properties of the liquid phase, and the grade efficiencies would be improved as the water cut increases, especially for smaller solid particles. What is more, the second hydrocyclone contributes more to the liquid-solid separation as the water cut reduces, and installing hydrocyclones in series is effective in improving the separating performances.

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