Available online at www.sciencedirect.com
ScienceDirect
Journal of Hydrodynamics
2012,24(1):116-123
DOI: 10.1016/S1001-6058(11)60225-4
www.sciencedirect.com/
science/journal/10016058

OIL/WATER SEPARATION IN A LIQUID-LIQUID CYLINDRICAL CYCLONE*

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(Received September 12, 2011, Revised November 8, 2011)

Abstract: The oil/water separation in a liquid-liquid cylindrical cyclone is experimentally studied in this article. The effects of the flow split-ratio and the flow rate on the oil/water separation performance are determined. From the experimental results, it is shown that with the increase of the flow split-ratio, the oil/water separation efficiency is enhanced at first, and an optimal flow split-ratio exists, beyond that optimal split-ratio, the watercut in the underflow keeps constant, while the oil content in the overflow begins to decrease. The process of the oil core structure formation and the phase distribution in the cyclone are determined by numerical simulations. Furthermore, the dependence of the separation efficiency on the Reynolds number and the flow split-ratio is investigated based on a dimensional analysis. A comparison between the predicted values and the experimental data shows a good agreement.

Key words: cylindrical cyclone, oil/water separation, flow split-ratio, flow rate, watercut

Introduction

With both the aging of onshore oil fields and the large-scale exploitation of offshore petroleum fields, the technology of the multiphase separation faces new challenges. According to the investigation of oil-gas-water separation devices in several major domestic oil fields[1], the multiphase separators are still mainly based on those conventional separating technologies, such as gravitational settlement and electrolytic separation. Due to the limitation of space and weight for devices to be installed in the deep-sea platform, it is important to develop compact and highly-efficient oil/water separators[2-4].

The combined separators, using several kinds of separating methods and taking advantages of their respective merits, can achieve the highly-efficient separation. Recently, they have attracted a keen interest from the petroleum industry. A combined separator using jointly the principles of gravity, expansion and centrifugation was developed in Institute of Mechanics, Chinese Academy of Sciences and it has successfully been applied to several onshore fields. A novel pipeline-style oil/water separator consisting of T-junctions and cylindrical cyclones is proposed recently[5]. This new separation system enjoys several advantages: such as compact geometry, high separation efficiency and easy maintenance. The cylindrical cyclone is one of the main components of the novel pipeline-style oil/water separator.

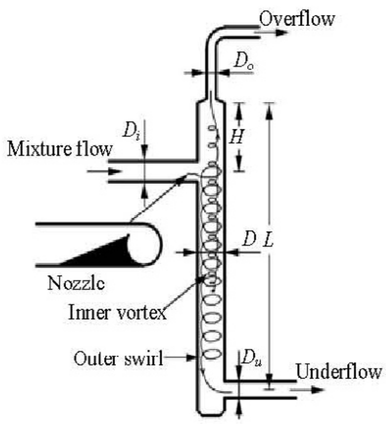

Fig.1 Schematic plot of the cylindrical cyclone

* Project supported by the Knowledge Innovation Program of the Chinese Academy of Sciences (Grant No. KJCX1-YW-21).
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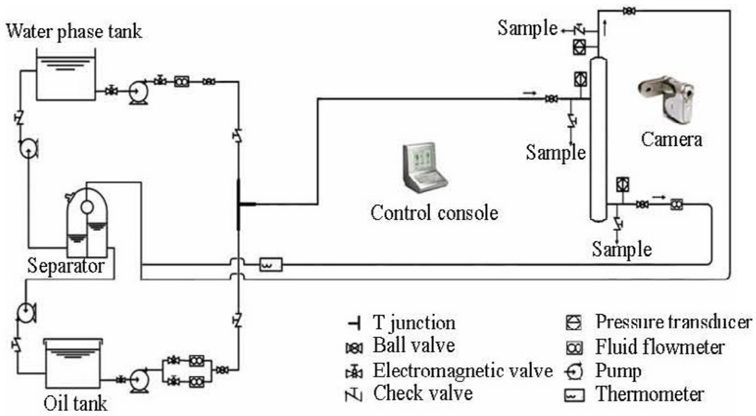


Fig.2 Schematic diagram of the test facility

The cylindrical cyclone is a vertical pipe with a tangential inlet and two outlets, one at the top and the other near the bottom, using the centrifugal separation technology and it is a simple, compact, low weight and low cost separator. Figure 1 shows a schematic plot of a cylindrical cyclone. Two kinds of immiscible mixture flow tangentially through the inlet into the cylindrical cyclone and a strong swirling flow field is formed. Due to the density difference, the denser component tends to be accumulated near the wall and spirals down to the bottom outlet (underflow), while the lighter component flows to the core region of the cylindrical cyclone to form a reverse flow and leaves the top outlet (overflow). The mechanism of the cylindrical cyclone is much like the traditional hydrocyclone, but with several advantages over the cylindrical cyclone, such as more stable oil core, greater capacity and less pressure loss. Initially, the cylindrical cyclones were used to separate the gas-liquid mixture, as the gas-liquid cylindrical cyclone[6,7]. They were successfully put into service in the petroleum industry. In the recent ten years, the liquid-liquid cylindrical cyclones were developed to separate the oil/water mixture[8,9]. Most of the related studies applied the Computational Fluid Dynamics (CFD) to predict the multiphase flow characteristics in the cylindrical cyclone[10-12]. Few experimental studies were focused on the flow field, the separation mechanism and the performance of the cylindrical cyclones[13,14]. In this article, an efficient liquid-liquid cylindrical cyclone is proposed, together with an experimental study to reveal the effects of the flow split-ratio and the flow rate on then oil/water separation performance in the liquid-liquid cylindrical cyclone. To further understand the detailed process of the oil/water separation and the phase distribution in the cyclone, numerical simulations were carried out. Finally, a simple model is built to predict the separation efficiency through a dimensional analysis.

1. Experimental set-up and procedures

Experiments were carried out on the multiphase flow facilities in Institute of Mechanics, Chinese Academy of Sciences. A schematic diagram of the oil/ water separation system is shown in Fig.2. The experimental set-up system mainly consists of three parts: (1) the feeding module, including the phase storage tanks, the liquid-phase pumps, the fluid flowmeters and the mixture separator, (2) the liquid-liquid cylindrical cyclone, made of transparent Perspex pipes to enable the visual observation of the oil/water distribution, which is the core components of the experimental system, as shown in Fig.3, (3) the data acquisition module, including the control console, the phase volume fraction testing device, the pressure transducers and a camera. In the experiment, the water and the oil are pumped from their respective storage tanks, and are introduced into the pipes via a T-junction. Before mixing, the water flow-rate is measured by an electromagnetic flowmeter and the oil flow-rate is measured by an oval gear flowmeter. The mixture flows along a 4 m long horizontal pipe (I.D. 0.05 m) and then is introduced tangentially into the cylindrical cyclone via a nozzle, located at the cyclone inlet of a section 20% of the inlet full cross sectional area. A sample device and a pressure transducer are located at the inlet and at each outlet. The valves in both the overflow and underflow tubes allow the control of the flow-rates of fliud leaving the cylindrical cyclone. A camera is placed to record the oil/water separating process. After being separated, both the overflow stream and the underflow stream flow into the separator to further separate under the gravitational force. Finally the oil and the water would flow back to the oil tank and the water tank, respectively.

All experiments were conducted at the room-temperature and the atmospheric outlet pressure. The main geometrical dimensions of the cylindrical cyclone used in this study are as follows: $D = 0.05$ m, $D_i = 0.05$ m, $D_o = 0.05$ m, $D_u = 0.04$ m, $L =$ 0.9 m, and $H = 0.1$ m, as shown in Fig.3. The water and the white oil are used as the test liquids. The primary phase is the water with a density of 998 kg/m^3 and a viscosity value of 0.001 kg/m·s. The density and the viscosity of the second phase oil are 840 kg/m^3 and 0.215 kg/m·s, respectively. The water flow-rates vary from 2.5 m^3/h to 8.75 m^3/h and the input oil volume fractions from 4% to 30%. We have a total of 195 experimental test points.

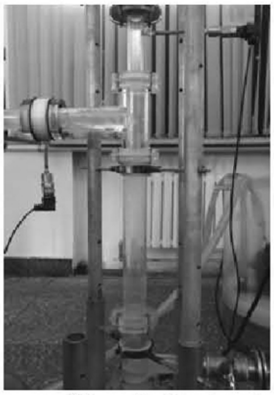


Fig.3 Picture of the cylindrical cyclone in lab

Fig.4 Oil core in the cyclone versus flow split-ratio (from 15.7% to 35.6%)

2. Results and analyses

2.1 *Effect of flow split-ratio on oil/water separation*

The flow split-ratio, defined as the ratio between the overflow liquid flow rate and the inlet liquid flow rate, is one of the most important operation parameters.

$$f_s = \frac{Q_{\text{over}}}{Q_{\text{inlet}}} \tag{1}$$

The effect of the flow split-ratio on the oil/water separation will be discussed in what follows.

2.1.1 Watercut in the underflow

Under given inlet conditions, a specified flow split-ratio is obtained through regulating the ball valves in outlet tubes. Figure 4 shows the effect of the flow split-ratio on the shape of the oil core in a sequence of photographs. The superficial water and oil velocities at the inlet are 0.743 m/s and 0.182 m/s, respectively. The inlet oil fraction is 19.7%. For a flow split-ratio equal or less than 15.7%, the oil/water mixture is separated by the centrifugal force after being tangentially introduced into the cyclone, but the shape of the oil core is not clear and a majority of the oil is drawn out with water from the underflow tubes. When the flow split-ratio is increased to 24.2%, a small quantity of oil can be seen in the underflow. At a flow split ratio of 27.4% or 31.4%, the shape of the oil core in the cyclone is very clear and only clean water is observed in the underflow. Then when the flow split-ratio reaches 35.6%, the oil entering into the cyclone is discharged directly out from the overflow tube, and no oil core is formed in the cyclone.

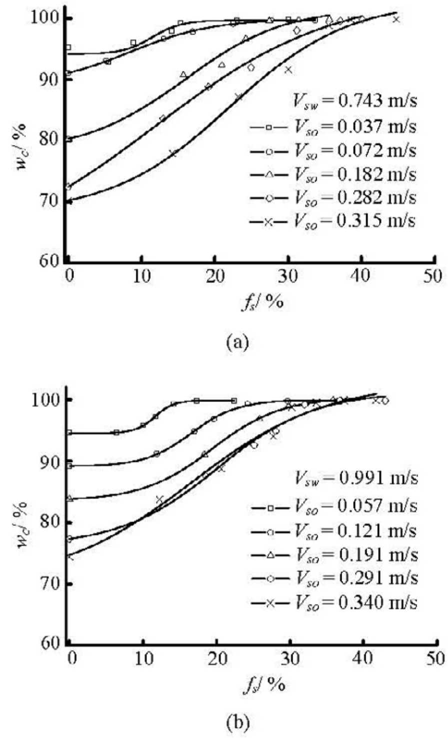


Fig.5 Watercut (W_c) in the underflow versus flow split-ratio

The effects of the flow split-ratio on the watercut in the underflow are shown in Fig.5. The watercut is plotted as a function of the flow split-ratio. During the experiments, the inlet water flow rate is fixed and the inlet oil flow rate increases gradually. Five constant superficial water velocities are considered in the studies with the input oil volume fractions varying from 4% to 30%. In Fig.5, the superficial water velocities are 0.743 m/s and 0.991 m/s, respectively. As can be seen, the effects of the flow split-ratio on the watercut in the underflow are similar. Taking the value of 0.743 m/s for an example, the superficial oil velocities are 0.037 m/s, 0.072 m/s, 0.182 m/s, 0.282 m/s and 0.315 m/s, which yield oil volume fractions of 4.7%, 8.8%, 19.7%, 27.5% and 29.8%, respectively. The experimental data points were obtained under a certain flow split-ratio. While the input oil fraction is fixed, with increasing the flow split-ratio, the watercut in the underflow increases, which means that increasing the flow split-ratio can improve the oil/water separation in the cyclone. It can also be observed that there is an optimal flow split-ratio in the cyclone, when only clean water is observed in the underflow and as soon as the flow split-ratio is greater than that value, no further improvement for oil/water separation is achieved. For different input oil volume fractions, these optimal flow split-ratios are also changed. Under these conditions, the optimal flow split-ratios are 15.3%, 22.5%, 27.4%, 37.1% and 38.5%, respectively. Under the lab conditions, through the separation in the cyclone, the oil volume fraction in the underflow can be reduced to a value below 1 000 ppm.

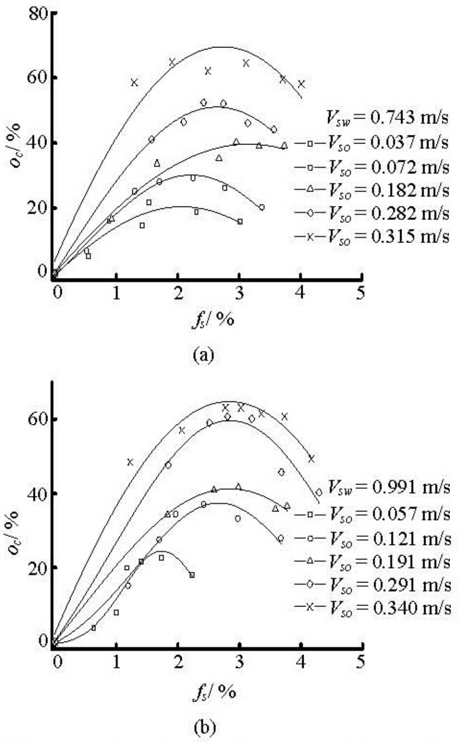


Fig.6 Oil content (o_c) in the overflow versus flow split-ratio

2.1.2 Oil content in the overflow

The overflow of the cylindrical cyclone contains a large amount of oil. Through the oil/water separation, not only we should have clean water in the underflow, but also we should have pure oil in the overflow or at least have a high oil volume fraction as high as possible. Figure 6 shows the effect of the flow split-ratio on the oil content in the overflow. Figures 6(a) and 6(b) show the cases for the superficial water velocities of 0.743 m/s and 0.991 m/s, respectively. It can be observed that the effects of the flow split-ratio on the oil content in the overflow are similar. Under a certain input oil volume fraction, with the increase of the flow split-ratio, the oil content in the overflow increases firstly and then decreases. This is because at a low flow split-ratio only a small amount of liquid ejects from the overflow outlet and the oil core formed in the center of the cyclone could not be entrained in the overflow stream successfully. While the flow split-ratio increases appropriately, much more liquid would outflow from the overflow outlet, carrying the oil core. So the oil content in the overflow increases. However, if the flow split-ratio is much higher, the oil core does not discharge with the overflow obviously, and some amount of water is mixed into the oil core and entrained in the overflow stream, resulting an increase of the oil content. From Fig.6, it can also be seen that there is an optimal flow split-ratio for the overflow. Comparing the optimal flow split-ratio for the overflow with that for the underflow, for the cases of low input oil volume fractions, such as 4.7%, 8.8% and 19.7% in the experiment, these two optimal flow split-ratios are similar, but when the oil volume fractions are as high as 27.5% and 29.8%, the optimal flow split-ratio for the overflow are much lower than that for the underflow.

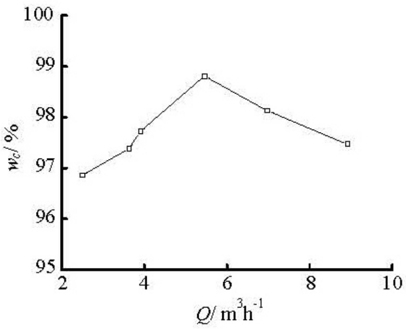


Fig.7 Effect of input flow rate on watercut in the underflow

2.2 *Effect of flow rate on oil/water separation*

The mixture flow rate versus the watercut under the same inlet oil volume fraction and the same flow split-ratio is illustrated in Fig.7. Six mixture inlet flow rates are considered. During the experiment, the oil volume fraction and the flow split-ratio are 10% and 20%, respectively. As the flow rate increases, the centrifugal force increases and hence the oil/water separation in the cyclone, and the watercut in the underflow. There is a peak point for the watercut. After that point, the continuous increase of the flow rate makes the watercut drop dramatically. These phenomena can be explained as follows: during the oil/water separation in the cyclone, a dramatic increase of the inlet flow rate can make the oil droplet broken-up due to the excessive shear-force and turbulence, and at the high flow rates, the dissolved gas in the mixture will be released at the low pressure (usually at the cylindrical cyclone axis) and hampers the separation.

2.3 *Numerical simulation*

So far we have discussed the oil/water separation performance in the cylindrical cyclone from a macroscopic view. Due to the limitation of laboratory experiments, it is difficult to simulate the multiphase flow characteristics in a cyclone very well. In order to further understand the detailed process of the oil/water separation and the phase distribution in the cylindrical cyclone, numerical simulations were carried out.

The numerical modeling of the cylindrical cyclone is based on the commercial CFD code "Fluent 6.3.26", which uses the finite volume method to discretize the differential equations describing the multiphase flow. For the strong swirling flow in a cyclone, the Reynolds Stress Model (RSM) is adopted to capture the anisotropic character of the turbulence in the cyclone. The Euler multiphase flow model is applied to simulate the oil/water two-phase flow. The mathematical model is given as follows.

2.3.1 Basic equations

Continuity equation

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q\right) + \nabla\bullet\left(\alpha_q \rho_q \boldsymbol{u}_q\right) = 0 \tag{2}$$

Momentum equation

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q \boldsymbol{u}_q\right) + \nabla\bullet\left(\alpha_q \rho_q \boldsymbol{u}_q \boldsymbol{u}_q\right) = -\alpha_q \nabla p + \nabla\bullet\overline{\overline{\tau}}_q + \alpha_q \rho_q \boldsymbol{g} + \sum_{p=1}^{n} K_{pq}\left(\boldsymbol{u}_p - \boldsymbol{u}_q\right) + \alpha_q \rho_q\left(\boldsymbol{F}_q + \boldsymbol{F}_{\mathrm{lift},q} + \boldsymbol{F}_{Vm,q}\right) \tag{3}$$

where α_q is the volume fraction of phase q, and the variables ρ_q and $\boldsymbol{u}_q$ represent the density and the velocity of phase q, respectively.

The turbulence model: the transportation equations of RSM are as follows:

$$\frac{\partial}{\partial t}\left(\rho\overline{u_i' u_j'}\right) + \frac{\partial}{\partial x_k}\left(\rho u_k \overline{u_i' u_j'}\right) = P_{ij} + D_{Tij} + \varphi_{ij} - \varepsilon_{ij} + F_{ij} \tag{4}$$

$$P_{ij} = -\rho\left(\overline{u_i' u_k'}\frac{\partial u_j}{\partial x_k} + \overline{u_j' u_k'}\frac{\partial u_i}{\partial x_k}\right) \tag{5}$$

$$D_{Tij} = -\frac{\partial}{\partial x_k}\left[\rho\overline{u_i' u_j' u_k'} + \overline{p\left(\delta_{kj} u_i' + \delta_{ik} u_j'\right)}\right] \tag{6}$$

$$\varphi_{ij} = \left(\overline{\frac{\partial u_i'}{\partial x_j} + \frac{\partial u_j'}{\partial x_i}}\right) \tag{7}$$

$$\varepsilon_{ij} = -2\mu\overline{\frac{\partial u_i'}{\partial x_k}\frac{\partial u_j'}{\partial x_k}} \tag{8}$$

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

The P_{ij} term represents the stress production, D_{ij} is the turbulent diffusion term, φ_{ij} is the pressure-strain term, ε_{ij} is the viscosity diffusion term and F_{ij} is the rotation production term.

2.3.2 Boundary conditions

The geometrical dimensions of the cylindrical cyclone in the numerical simulations are shown in Fig.1. A total of 3.5×10^5 mesh elements are used. The water and the oil are used as the test liquids. At the entrance, a velocity-inlet condition is specified. The turbulence parameters and the normal velocities and the phase volume fraction of all phases are properly specified. The boundary conditions for the underflow and the overflow are defined based on the flow rate and the pressure-outlet. No-slip boundary conditions are assumed on all walls. The SIMPLE algorithm is used for the pressure-velocity coupling and the second-order upwind scheme is applied to interpolate the field variables on the faces of the control volumes. The iterative procedure continues until the continuity residual is reduced to 1.0×10^{-6} and the phase flow rates for the two outlets are monitored to judge whether the flow in the cylindrical cyclone is steady or not.

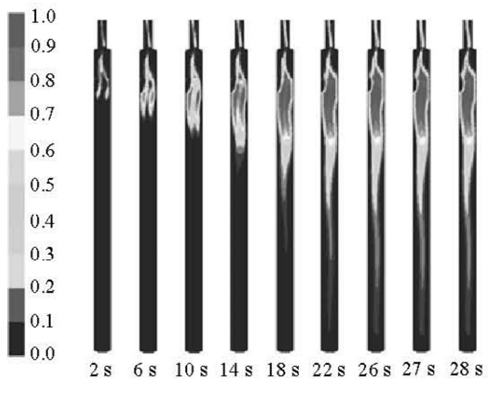


Fig.8 Transient development of oil core structure from numerical simulations

2.3.3 Numerical results

Figure 8 shows the transient development of the oil core structure in the cylindrical cyclone from numerical simulations. The inlet superficial velocities of water and oil are 0.5 m/s and 0.1 m/s, respectively and the differential pressure between the underflow and the overflow outlet is 0.75 kPa, according to the experimental measurements. It can be observed that the cylindrical cyclone is initially filled with water and as the oil/water mixture is introduced into the cyclone, due to the presence of centrifugal forces, the water phase flows to the cyclone's wall while the oil phase is accumulated at the center. After about 26 s of calculation, the phase distribution in the cylindrical cyclone becomes fairly stable and the oil core deforms very little.

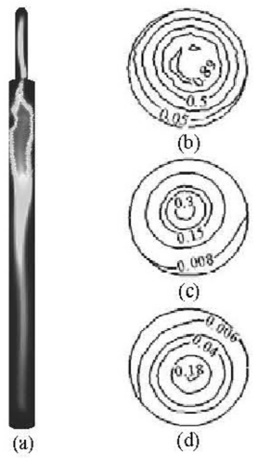


Fig.9 Volume fraction contour of oil phase

The cross-sectional distributions of the oil phase in the cyclone are given in Fig.9. Figure 9(a) shows the oil core structure and the other three figures (b, c and d) show the contour lines of the oil phase in the cross sections located at distances of 2, 6 and 10 pipe diameters away from the horizontal inlet, respectively. As can be seen, with the increase of the distance away from the inlet, the oil core turns to be more slender and finally disappears at the upper part of the underflow. In the same cross section, the oil volume fraction is higher at the center and much lower near the cyclone wall. The phase distribution in the cyclone is unsymmetrical because of the single inlet arrangement.

Experiments were conducted to validate the above model. Figure 10 shows the comparison of the watercut in the underflow between the numerical results and the experimental data. The triangle dots are the experimental data while the solid line represents the simulation solutions. When the flow split-ratios are higher than 24%, the results show a good agreement. For those lower flow split-ratios, the largest relative error between the numerical simulation and the experimental data is no more than 2.7 percent, which indicates that the above model can predict the oil/water two-phase flow and the separation in the cylindrical cyclone quite well.

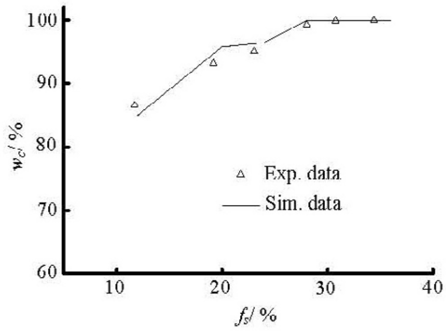


Fig.10 Comparison between numerical simulation and experimental data

3. Prediction of separation efficiency

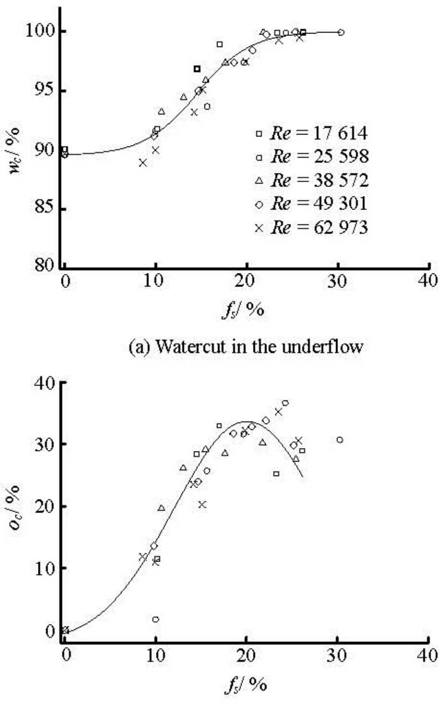
The separation efficiency of the cylindrical cyclone depends on many parameters, mainly including structure parameters, operation parameters and physical parameters[15]. The structure parameters are mainly about the geometrical dimensions of the cylindrical cyclone, such as the cyclone diameter D, the height of the cylinder H, the inlet diameter D_i, the inlet slot area ratio A, the overflow diameter D_o, the underflow diameter D_u. The operation parameters include the inlet velocity v_i, the inlet oil volume fraction ε_o, the flow split-ratio f_s and the oil droplet diameter d_o. The physical parameters include the water viscosity μ_w, the water density ρ_w, the oil viscosity μ_o and the density ρ_o. Thus, the separation efficiency η can be expressed as

$$\eta = f\left(v_i, \mu_w, \rho_w, \mu_o, \rho_o, \varepsilon_o, d_o, f_s,\right.$$
$$\left. D, H, D_i, A, D_o, D_u, \ldots\right) \tag{10}$$

For a cylindrical cyclone with fixed dimensions and under certain inlet conditions, through a dimensional analysis, the following equation can be obtained

$$\eta = f\left(Re, f_s\right) \tag{11}$$

where $Re = \rho_w D v_i / \mu_w$. Therefore, Eq.(11) is a function of the Reynolds number and the flow split-ratio. The relationships between the flow split-ratio and the oil/water separation, under the same input oil volume fraction, are presented in Fig.11. The inlet oil volume fractions are fixed at about 10%.



(a) Watercut in the underflow

(b) Oil content in the overflow

Fig.11 Relationships between flow split-ratio and oil/water separation

As can be observed from Fig.11(a), for different Reynolds numbers, the function relationships between the flow split-ratio and the watercut in the underflow are the same. The solid curves are fitted to the experimental data plot. Furthermore, all the curves obey the same Boltzmann distribution, which can be expressed as

$$w_c = A_2 + \frac{A_1 - A_2}{1 + e^{[(f_s - x_0)/dx]}} \tag{12}$$

where A_1, A_2, x_0 and dx are parameters determined by the initial input conditions. For example, when the Reynolds number is 17 614, the regression equation is,

$$w_c = 99.959 - \frac{9.899}{1 + e^{[(f_s - 13.039)/1.865]}} \tag{13}$$

A comparison of the experimental values and the calculated ones using Eq.(12) is shown in Fig.12(a). Most of the experimental values are well within the ±2% deviation region. A reasonable fit is found between the experimental values and the calculated ones.

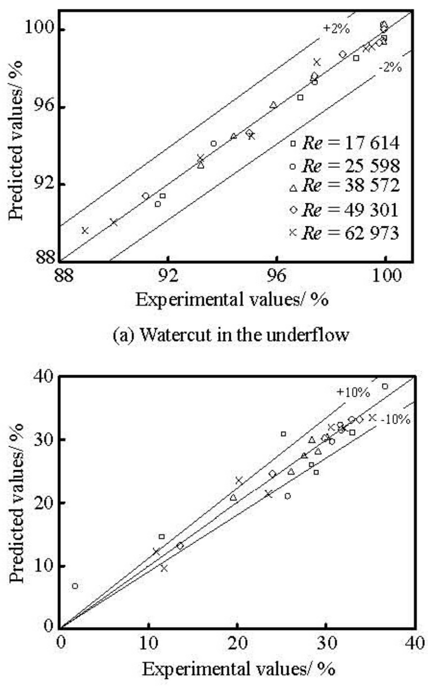
The relationship between the flow split-ratio and the oil content in the overflow is presented in Fig.11(b). It should be noted that the experimental data points are in the Gauss distribution as

$$o_c = A_1 + \frac{A_2}{1.253w} e^{-\frac{2(f_s - x_0)^2}{w^2}} \tag{14}$$

where A_1, A_2, w and x_0 are parameters determined by the initial input conditions. Also taking a Reynolds number of 38 572 for an example, the regresseion equation is,

$$o_c = -1.818 + 35.117 e^{-\frac{2(f_s - 21.367)^2}{313.216}} \tag{15}$$

Figure 12(b) shows the comparison of experimental values of the oil content in the overflow and the calculated ones obtained from Eq.(14). As can be seen, Eq.(14) can describe the majority of the experimental data within ±10%.



(a) Watercut in the underflow

(b) Oil content in the overflow

Fig.12 Comparison of experimental and predicted values of oil/water separation in cylindrical cyclone

4. Conclusions

An experimental study is carried out to simulate the oil/water separation in a liquid-liquid cylindrical cyclone. The effects of the flow split-ratio and the inlet flow rate on the separation efficiency are investigated experimentally. Numerical simulations are also carried out to further understand the process of the oil core structure formation and the phase distribution in the cylindrical cyclone. From the results, the main conclusions can be drawn as follows:

(1) The flow split-ratio is a key parameter affecting the oil/water separation efficiency in the liquid-liquid cylindrical cyclone. The separation efficiency increases with increasing the flow split-ratio. But there is an optimal split-ratio under a certain inlet condition. For flow split-ratios higher than the optimal one, clean water is seen in the underflow stream and the watercut keeps constant, while the oil content in the overflow begins to decrease as the split-ratio further increases.

(2) An appropriate increase of the inlet flow rate can improve the oil/water separation. However, an extreme high flow rate may hamper the separation due to the oil/water emulsification and the dissolved gas.

(3) Due to the presence of centrifugal forces, the oil phase after being introduced into the cylindrical cyclone is accumulated at the center. The phase distribution tends to be fairly stable about several seconds later. The watercut in the underflow as seen from numerical results are in good agreement with the experimental data, indicating that the numerical model can predict the oil/water two-phase flow in the cylindrical cyclone quite well.

(4) Through a dimensional analysis, the separation efficiency is a function of the Reynolds number and the flow split-ratio. In the whole range in the experiment, both the experimental data and the predicted curves exhibit the same trend and a good agreement is obtained between the predicted values and the experimental data, especially for the watercut in the underflow, with a deviation within ±2%.

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