Oil-water separation efficiency and fluid mechanics of a hydrocyclone

Xiangzhong Fan[1, a]
[1]School of Petroleum Engineering, China University of Petroleum, Beijing 102249, China;
[a]fanxiangzhong_2016@163.com

Keywords: Computational fluid dynamics; oil-water separation; fluid mechanics; hydrocyclone;

Abstract. Hydrocyclone separation technology as a kind of effective oil water separation technology, has been applied in the oil industry. The paper proposes numerical simulation of computational fluid dynamics which combine Reynolds stress model and Euler multi-phase model together, and discusses the operating conditions and material properties making influence on the efficiency of oil-water separation of a hydrocyclone by Fluent6.3. The simulation shows that the hydrocyclone with diameter 50mm, two inlets, and a single cone angle 5.5°, has an optimum distribution ratio 10%，a best concentration of oil droplets 0.5%. Under the above conditions, the hydrocyclone could remove more than 80% per 15 μm oil droplets, and the separation of oil droplets cut size is 9.2 μm for 50% separation efficiency. Through simulated prediction of separation efficiency corresponding to the measured values, the error is obtained less than 15%.

Introduction

Hydrocyclone separation technology, as a kind of effective oil water separation technology, has been applied in the oil industry due to the compact equipment without adding chemical agent[1-2]. Although the structure of Hydrocyclone separator is simple, many parameters variable affect the separation efficiency, such as import flow velocity, split ratio, oil droplet size, oil droplet concentration and so on. So many people do the experiments, in order to optimize parameters of the cyclone separator structure and operating conditions[3-5]. Because of many relevant variable parameters, there are many problems, such as workloads of experimental research, high cost and uncertainty on industrial amplification[6].

With the rapid development of computer technology, computational fluid dynamics method has become an important means for hydrocyclone due to the high speed and low cost[7-10]. Research of hydrocyclone separation mainly concentrated on solid-liquid aspect. The literature[11] proposed hydrocyclone with different diameter of spigots corresponding to the curve of separation gravel. The literature[12] simulated separation performance for 50mm hydrocyclones and 76mm hydrocyclones for ash by computational fluid dynamics. The literature[13] utilized computational fluid dynamics to optimize the structure of the hydrocyclones. As for oil-water separation, The literature[2] simulated dehydrate efficiency of different diameter of oil. But there are little research on operating conditions and material properties for dehydrate efficiency by computational fluid dynamics.

A full glass cyclone separator was established to make oil-water separation. Dynamic particle analysis instrument is used to analysis the flow field inside cyclone and droplet distribution[14]. In this paper, operating conditions including inlet velocity and separation ratio and material properties including droplet size and concentration of oil droplets have influence on dehydrate efficiency. Statistical method was used to study the relationship between the oil-water separation efficiency and operating parameters or physical properties of the hydrocyclone, which provides the basis for promoting the application of cyclone in oil-water separation.

Model Establishment

A. Parameters of Hydrocyclone

The oil-water cyclone separator is a single cone with double inlet cyclone. The parameters of the cyclone separator are as Table.1.

Table 1 Parameters of the cyclone separator

Parameters	number
Cyclone diameter	50mm
Cylindrical length	50mm
Inlet diameter	13mm
Underflow pipe diameter	19mm
Underflow pipe length	900mm
Overflow diameter	8mm
Taper angle	5.5°
Taper length	322mm

B. Model Arithmetic

Use commercial Fluent 6.3 software to simulate. Adopt continuity equation and Navier-Stokes equation, and import Reynolds Stress Model to get a solution. Because oil-water separation refer to two-phase fluid, so this paper utilizes Mixed Euler Equation[15], which assumes that all of the phase with the same stress field. As for any phase, we solve the momentum equation and continuity equation.

Operating parameters and material properties as two variable parameters in operation process. Operating parameters are inlet flow rate and split ratio. Among them, inlet flow rate correspond to fluid entering speed 4.18~20.93m/s, where split ratio refer to the ratio of excessive traffic and inlet flow rate. Material parameters is the ratio of oil droplet size and concentration of oil droplets. During the process of simulation, when a parameter change, other parameters stay constant. Specific parameters are as follow Table.2.

Table 2.Parameters of the cyclone separator

	Operating Parameter		Material Parameters	
	Inlet Flow Rate	Split Ratio	Oil Droplet Size	Concentration of Oil Droplets
Value	2000~10000L/h	2%~20%	5~30um	0.05%~5%

Use pressure-based solver and separation method to simulate and calculate. The grid is unstructured grids. Due to the complexity of flow field within the cyclone, it is difficult to ensure flow direction and the grid to be consistent. In order to solve this problem, the discrete method of the simulation control equation use second-order upwind scheme. Entrance is for speed, export is for pressure, and wall is for non-slip boundary. while the density of water phase is 1000kg/m3, the viscosity is 0.001003kg/ms, the density of oil phase is 860kg/m3, and the viscosity is 0.0033kg/ms.

Results and Discussion

A. The effect of split ratio on separation efficiency

Figure 1 simulate the effect of split ratio on separation efficiency and inlet pressure with 23 μm oil droplets size under different inlet flow rate and different oil concentration. When inlet flow rate F_i is 2000L/h, concentration of oil droplets C_{oil} is 0.5% and split ratio R_s growing from 2% to 25%, we can get the separation performance growing from 2.90% to 98.26%. When concentration of oil droplets C_{oil} is 1%, we can also obtain a similar rule. From what has been discussed above, when the inlet flow rate F_i stay constant, the separation efficiency of cyclone will increase as the split ratio increases.

When the split ratio R_s is less than 5%, separation efficiency is low and increases slowly as split ratio R_s increases. This shows that if the oil droplets size Soil is little enough, oil droplets may flow out though underflow orifice. When the split ratio R_s is more than 10%, separation efficiency is still increasing with the increase of split ratio, but the increase degree rise only sluggishly. This indicates that, only a small increase of separation efficiency in influenced by rising split ratio R_s.

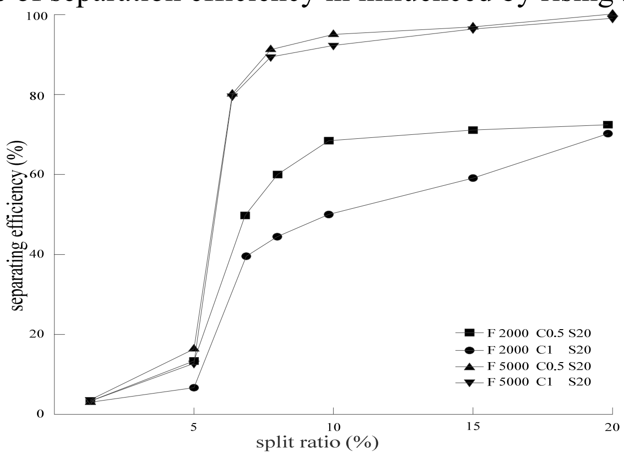

Figure 1. Effect of split ratio on separation efficiency

B. The effect of inlet velocity on separation efficiency

As shown in Figure2, when the split ratio R_s=10%, inlet velocity V_i has effect on separation efficiency and pressure. As for oil droplets size S_{oil} is 20μm and concentration of oil droplets C_{oil} is 0.5%, When the inlet velocity V_i is growing from 4.37m/s to 20.93m/s, the separation performance growing from 69.32% to 99.75%. As for oil droplets size S_{oil} is 10μm and concentration of oil droplets C_{oil} is 0.5%, the separation performance growing from 33.65% to 94.21%. When the concentration of oil droplets C_{oil} is 1%, there exit a similar rule. When the concentration of oil droplets C_{oil} is 0.5% and inlet velocity V_i is 4.37m/s, the threshold of separation corresponds to 15μm oil droplets size S_{oil}, while inlet velocity V_i is 10.46m/s, the threshold of separation corresponds to 9.2μm oil droplets size S_{oil}.

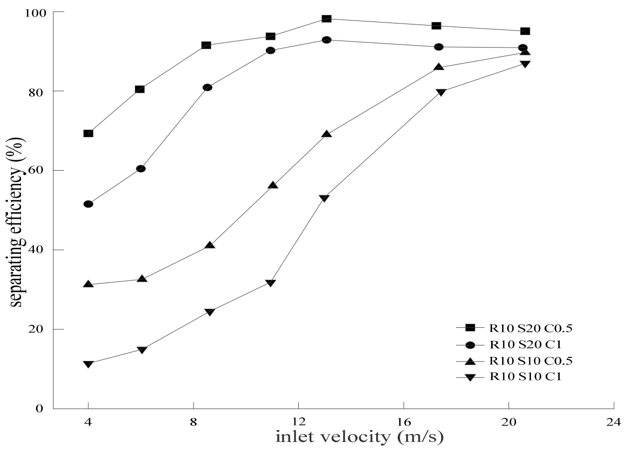

Figure 2. Effect of inlet velocity on separation efficiency

Inlet velocity V_i will lead to tangential velocity increase, thereby increasing driving force of oil-water separation. Although the separation efficiency increases with the increase of flow velocity, inlet velocity increase will enlarge water pressure. All this lead to drop pressure from import to underflow orifice rise, so that operating cost increasing rapidly.

C. The effect of oil droplets size on separation efficiency

Generally speaking, different size of oil droplets has different separation efficiency in cyclone separator. Figure 3 simulates separation efficiency of different size of oil droplets under the diversion ratio 10%. For the conditions of inlet flow rate F_i =2000L/h and concentration of oil droplets C_{oil} =0.5%, When the oil droplets size S_{oil} is growing from 5 μm to 30 μm , separation efficiency will grow from 15.64% to 92.45%; but for the conditions of inlet flow rate F_i =5000L/h and concentration of oil droplets C_{oil}=0.5%, separation efficiency will grow from 26.47% to 99.76%. When concentration of oil droplets C_{oil} is 1%, we can also obtain a similar rule. From what has been discussed above, when oil droplets size S_{oil} is more than 25um, the inlet flow rate F_i has less effect on the separation efficiency. So we can take action to increase oil droplets size will improve the separation efficiency.

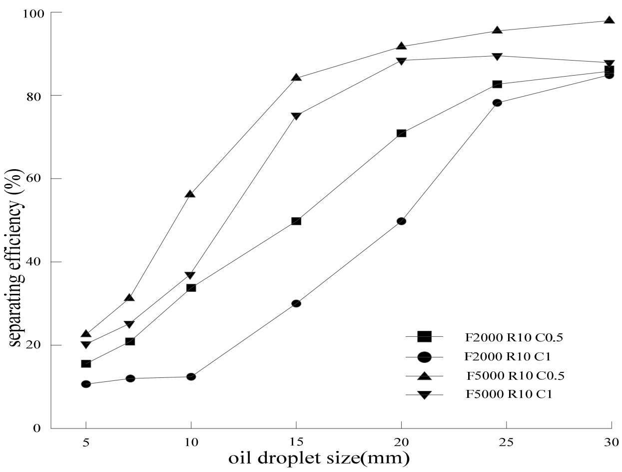

Figure 3. Effect of oil droplets size on separation efficiency

D. The effect of concentration of oil droplets on separation efficiency

In the past years, there is little research on the effect of concentration of oil droplets C_{oil} to separation efficiency. Because the range of oil droplets size 130 μm < S_{oil} < 150 μm is large, and inlet flow rate F_i is quite high, there is less relativity between concentration of oil droplets C_{oil} and separation efficiency. But for smaller oil droplets size, concentration of oil droplets C_{oil} will significantly affect the separation efficiency. As shown in Figure 4, when the concentration of oil droplets C_{oil} is less than 0.5%, separation efficiency almost stay constant as concentration of oil droplets C_{oil} growing. When the inlet flow rate F_i is high enough, such as 5000L/h, inlet velocity V_i =11.21m/s, and a larger oil droplets size S_{oil} 20um, concentration of oil droplets C_{oil} has a little effect on separation efficiency. But with the inlet flow rate F_i or oil droplets size S_{oil} decreasing, concentration of oil droplets C_{oil} has obvious influence on separation efficiency. This indicates that the existence of threshold for concentration of oil droplets C_{oil} is 0.5, and if less than it, concentration of oil droplets C_{oil} has little or no effect on separation efficiency.

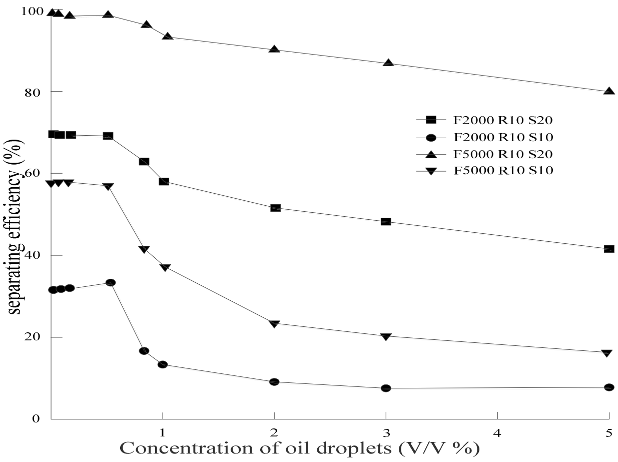

Figure 4. Effect of concentration of oil droplets on separation efficiency

F. The relationship between the simulation results and experimental results

Concluded from the above discussion, the separation efficiency of the hydrocyclon is affected not only by the operating parameters, such as inlet flow rate and split ratio, but also by material properties, such as oil droplet size and concentration of oil droplets. This effect is very complex.

According to simulation data Figure 1~4, with the statistical software STA-TISTICA6, the relationship is obtained between the separation efficiency and the operating conditions and the material properties by the multinomial fitting method.

$$\begin{aligned}\omega &= 0.01F_i + 12.759R_s - 20.703C_{oil} + 6.133S_{oil}\\ &-0.004R_s \times C_{oil} + 0.032R_s \times S_{oil} + 0.325C_{oil} \times S_{oil}\\ &-0.448R^2 + 1.896C^2 - 0.077D^2 - 128.498\end{aligned} \quad (1)$$

where: ω is the separation efficiency for single oil droplet(%), F_i is inlet flow rate(L/h), R_s is the split ratio(%), C_{oil} is the concentration of oil droplets(%,V/V), S_{oil} is oil droplet size(μm). Separation efficiency response to different oil droplet size is calculated according the formula 1. Then we can calculate the separation efficiency of original water by formula 2.

$$SE = \sum_i \omega_{S_{oil}(i)} \theta_i \quad (2)$$

Where SE is separation efficiency for all, $\omega_{S_{oil}(i)}$ is the separation efficiency of S_{oil} oil droplet size, and θ_i is the volume percent of S_{oil}. The relationship between the simulation results and experimental results is shown as Figure 5. Simulation of separation efficiency is consistent with the experimental results, and the error is within 15%.

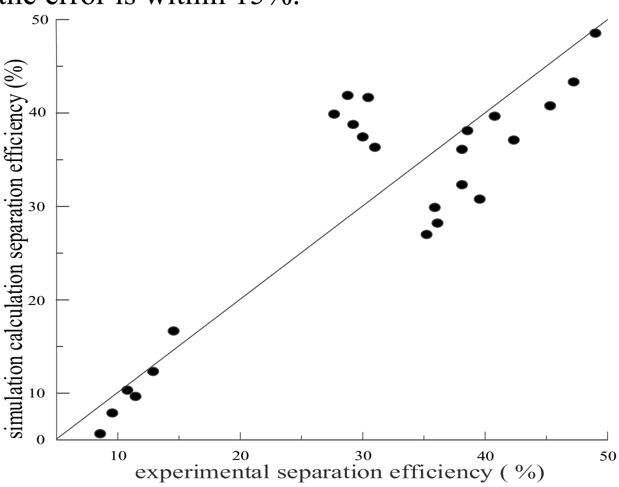

Figure 5. Relationship between the simulation results and experimental results

Conclusion

Use computational fluid dynamics which combine Reynolds stress model and Euler multi-phase model together. Discusse the operating conditions and material properties influence the efficiency of oil-water separation of a hydrocyclone by Fluent6.3. The following conclusions are arrived: the hydrocyclone with diameter 50mm, two inlets, and a single cone angle 5.5° , has an optimum distribution ratio 10% and a best concentration of oil droplets 0.5%(V/V). Under the above conditions, the hydrocyclone could remove more than 80% per 15 μm oil droplets, and the separation of oil droplets cut size is 9.2 μm for 50% separation efficiency. Through simulated prediction of separation efficiency corresponding to the measured values, the error is obtained less than 15%.

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