Field Analysis and performance study of an integrated hydrocyclone for degassing and deoiling

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Abstract. To solve the problem of oil and water being unable to be efficiently separated under gas-containing conditions, an integrated cyclone capable of efficiently separating the three phases of oil, gas and water is designed based on the principle of cyclonic separation. Flow field analysis and separation performance study of different treatment amounts, split ratios and oil contents were conducted, and the effects of gas-phase distribution, oil-phase distribution, pressure field and separation efficiency in the cyclone under different conditions were shown. Results indicate that show that the outlet pressure drop, the increase rate and the separation efficiency gradually increase as the processing capacity increases. As the split ratio increases, the oil-phase separation efficiency gradually decreases, and the pressure loss at the bottom flow port gradually increases. The experiment and simulation show that the separation efficiency is the highest when the sum of the internal overflow splits is 50%, and the optimal processing capacity is 23 m$^3$/h. The cyclone has a strong adaptability to liquids with different conditions, and the separation efficiency can reach 98.6%.

1. Introduction

Hydrocyclone has the advantages of small equipment size, easy operation and high separation efficiency [1] and is widely used in chemical, oilfield, environmental protection and other fields [2]. A large amount of oil is produced during crude oil extraction and includes associated gas composed of elements such as methane, ethane, butane and hydrocarbons [3]. The existence of associated gas is inconsistent with ground construction. Firstly, if an effective associated gas recovery system is not established, then the associated gas is invalidated and vented and will cause environmental pollution and waste of resources[4]. Oil and water are incompatible with each other in the oil–gas–water mixture, the separation of three-phase flow is highly complicated [5], and the separation performance of the hydrocyclone is greatly affected by the structural mode, structural parameters and operating parameters, such as split ratio and throughput[6-8]. Among them, treatment capacity is one of the most important parameters. Several domestic scholars have performed related research on oil, gas and water three-phase cyclone separators. Zhou [9] used the traditional double-cone hydrocyclone and inner-cone cyclone as basis and then introduced an oil–gas–water three-phase separation cyclone after certain improvements. Zheng [10] designed an oil–water–gas three-phase cyclone separator. The flow device separates the inner and outer layers and discharges from the central annular gas-phase outlet through the lifting of the cone angle and radial pressure. Taking degassing and deoiling integrated cyclone as the research object, conducted
numerical simulation and experimental research on internal flow field characteristics and separation performance, analysed the effects of pressure and efficiency of a three-phase separation cyclone with different treatment volumes and split ratios, and proved its feasibility and scope of application.

2. Physical model and separation principle
The fluid domain model of the degassing and deoiling integrated cyclone is shown in Figure 1. The main characteristic of the hydrocyclone is based on the principle of swirl separation through the ingenious cooperation of a pressurising element and a variable-diameter separation pipe diversion device in a sealed sleeve. The axial and radial multistage separation modules are formed, thus achieving multistage three-phase medium separation in the same device.

![Figure 1 Fluid domain model](image1)

(1) Primary overflow (2) Inlet of mixture (3) Secondary overflow (4) Gas–liquid separation chamber (5) Secondary oil–water separation chamber (6) Secondary oil-phase diversion hole (7) Secondary pressuriser (8) Primary oil–water separation chamber (9) First oil-phase diversion hole (10) Primary booster (11) Guide hole (12) Bottom flow

The working principle is shown in Figure 2. The mixture of oil, gas and water enters the gas–liquid separation chamber and separates the gas and liquid under the action of centrifugal force. The gas phase is discharged from the device through the primary overflow along the outer wall of the gas–liquid separation tube. Degassing after the mixture under the action of pressure along the guide hole is introduced at the bottom of the oil–water separation chamber interior. The internal pressurisation device can implement tangential acceleration of liquid. The oil phase in the oil–water separation chamber in the migration discharge device to the axis position along the oil-phase flow guides the complete separation of oil–water mixture level. Incomplete separation of oil–water mixture continues to affect the top direction along the pressurisation catheter, the spiral acceleration to secondary flow, the pressure loss of the accelerating port on the compensation after entering the secondary oil/water separation chamber interior ministry and the secondary separation of oil and water. At this time, the light oil phase after secondary separation merges with the light oil phase after primary oil–water separation along the overflow port of the light phase and is discharged from the secondary overflow device. The water phase continues to move to the top in the two-stage oil–water separation chamber and is discharged through the bottom flow device to ensure the efficiency of oil removal in the form of two-stage oil–water separation.

![Figure 2 Schematic](image2)

3. Grid division and independence test
Gambit software was used to mesh the integrated cyclone for degorging and deoiling. Compared with nonstructural grids, structural grids have the advantages of fast computing speed, high accuracy and strong convergence. Hence, hexahedral structural grids were selected to mesh the target cyclone.
Table 1. Number of grids divided by different levels

| Grid level | Level-1 | Level-2 | Level-3 | Level-4 | Level-5 |
|------------|---------|---------|---------|---------|---------|
| Grid number| 726802  | 964589  | 1183260 | 1358549 | 1566588 |

Pressure drop is an important index that reflects the separation performance of hydrocyclone. Under the condition that other boundary conditions remain unchanged, the pressure drop of bottom flow is regarded as the evaluation index of the grid independence test. Figure 3 shows the comparison curve of the bottom flow pressure drop of different grid levels. The pressure drop declines first and then increases with the increase in the grid levels. When the grid level is level 3, the pressure drop no longer decreases with the increase in the number of grids. Level 3 was selected for numerical simulation, as shown in Figure 4.

Figure 3. Pressure drop at the outlet of water phase at different grid levels.

Figure 4. Mesh detail diagram

4. Simulation parameter setting

The simulated media are oil, gas and water, and their parameters are set as fixed values in the research process. The specific values are set in accordance with the sample solution produced at the wellhead of an oilfield to prevent the physical parameters of the medium from influencing the analysis of the separation performance of the cyclone. The continuous phase is water with a density of 998.2 kg/m$^3$ and a viscosity of 0.89 MPa·s. The discrete-phase media are oil and gas, in which the density of oil is 889 kg/m$^3$ and the viscosity is 1.06 Pa·s; the density of gas is 0.668 Pa·s and the viscosity is $1.087 \times 10^{-5}$ Pa·s. The inlet boundary condition is the velocity inlet, and the calculated processing capacities are 19, 21, 23, 25 and 27 m$^3$/h (as determined by the on-site processing demand).

The corresponding inlet velocity is

$$ Q = v_i A \quad (1) $$

Where $Q$ is the inlet flow rate, m$^3$/h; and $A$ is the inlet overflow area.

For deoiling hydrocyclones, the density of the discrete medium is smaller than that of the continuous-phase medium. For the separation medium with minimal oil in the water, the overflow shunt ratio should be greater than the total oil concentration. The range of the overflow shunt ratio should be determined as $F=35\%-55\%$. The sum of the shunt ratio of the primary and secondary overflow outlets is within the range of 35$\%$–55$\%$. When the diversion ratio of the primary overflow outlet is fixed at 15$\%$, the diversion ratio of the secondary overflow outlet is 20$\%$–40$\%$. The oil-phase volume fraction was set to range from 5$\%$ to 25$\%$ (value: 5$\%$, 10$\%$, 15$\%$, 20$\%$, 25$\%$) to represent the different oil contents of the mixed medium. The incompressible flow field was solved mainly by using the calculation selection pressure benchmark algorithm implicit solver steady-state, turbulent flow calculation model for the Reynolds stress model, the comprehensive stability of the calculation precision, simulation calculation with first-order windward format to pressure and velocity coupling using the SIMPLE algorithm; these methods can also be used in the pressure flow field. The wall
boundary condition was assumed to have no leakage and no slip wall, and the residual precision was set to $1 \times 10^{-6}$.

5. Analysis results

5.1. Effect of handling capacity on flow field characteristics and separation performance

As shown in Figure 5. The pressure drop of the primary overflow port presents a trend of slow rise with an increase in the treatment capacity. When the treatment capacity increases to 23 m$^3$/h, the pressure drop of the secondary overflow port evidently rises, and the critical point of the pressure drop of the bottom flow port sharply rises when the treatment capacity reaches 25 m$^3$/h. With the gradual increase in the processing capacity, the pressure drop of each region in the cyclone presents an increasing trend, indicating that the pressure drop of the cyclone constantly changes with the change in the processing capacity. A great inlet flow rate corresponds to greater velocity in the cyclone and highly intense friction and collision among the fluids; the latter causes the pressure loss. Therefore, under normal circumstances, a great inlet flow rate corresponds to great velocity and pressure.

![Figure 5. Comparison curve of pressure loss at different treatment volumes](image1)

As shown in Figure 6. When the capacity is 19–21 m$^3$/h, S$_2$ section secondary oil-phase diversion pipe still has gas accumulation. This condition suggests that the inlet velocity cannot meet the demand of the gas-phase separation, does not have a part of the gas-phase separation with the mixture flow liquid–liquid separation chamber and has the feature of S$_3$ section centre phase distribution and gas from the oil-phase outlet device. These characteristics will affect the separation efficiency. When the processing capacity is greater than 23 m$^3$/h, no gas-phase distribution exists at the rear end of the device, that is, most of the gas phase is discharged from the gas-phase outlet. The inlet velocity increases, that is, the tangential velocity increases. The centrifugal force provided for the migration of the gas phase increases, which is conducive to the gas-phase separation of the cyclone.

![Figure 6. Gas-phase volume fraction distribution cloud map at different treatment volumes](image2)
The cloud diagram of oil-phase volume fraction distribution of cyclone with different treatment capacities was obtained by simulation, as shown in Figure 7. The oil-phase separation effect gradually improves with the increase in treatment capacity, but when the treatment capacity rises to 27 m$^3$/h, the oil-phase separation effect is lower than that at 23–25 m$^3$/h. The gas core that accumulates in the centre becomes increasingly obvious. In other words, the oil phase accumulates obviously when the treatment volume is considerably large, but the gas phase remains minimal in the separation chamber when the flow rate is excessively high. This condition results in incomplete gas-phase separation and partial gas phase flowing into the liquid–liquid separation chamber along with the liquid, affecting the separation effect of oil and water.

As shown in Figure 8, it can be seen that the two-phase separation efficiency shows a gradual upward trend. When the flow rate increases to 23 m$^3$/h, the oil-phase separation efficiency curve tends to be flat and no obvious upward change occurs. When the flow rate increases to 25 m$^3$/h, the gas-phase separation efficiency and oil-phase separation efficiency both show a slight downward trend. This is because when the flow rate increases, the rate of gas phase migration to the center increases, which is conducive to the accumulation of gas phase. Meanwhile, the increased flow rate is conducive to the formation of oil core and the separation of different media. However, when the flow rate is too high, the gas phase stays too short in the gas-liquid separation chamber, that is, part of the gas phase flows with the liquid to the liquid-liquid separation chamber before the separation process is completed, leading to the decrease of the gas phase separation efficiency, which will also lead to the decrease of the oil phase separation efficiency.
5.2. Effects of shunt ratio on flow field characteristics and separation performance

The shunt ratio of the hydrocyclone is respectively the primary overflow port and the secondary overflow port, when simulating the effect of shunt ratio on hydrocyclone separation performance, the shunt ratio of the primary overflow port has been determined to be 15%, and the shunt ratio of the secondary overflow port has been adjusted to change within the range of 20%~40%, and the total shunt ratio has been adjusted within the range of 35%~55%, the influence of the shunt ratio on the separation performance of the cyclone is analyzed. The cloud diagram of oil phase volume fraction distribution of cyclone with different shunt ratios was obtained by simulation, as shown in Figure 9. It can be seen that the separation effect of oil phase is improved with the increase of the shunt ratio. When \( F = 35\% \), the separation effect is not obvious. A large amount of oil phase is discharged from the bottom flow port, which fails to achieve the required separation effect. However, the separation effect did not improve with the continuous increase of the overflow shunt ratio, that is, the separation effect did not significantly improve with the increase of the shunt ratio when \( F \) was greater than 45%.

![Figure 9. Cloud diagram of oil phase volume fraction distribution in hydrocyclones with different shunt ratios](image)

The oil phase volume fraction curves at section S1 of the cyclone with different shunt ratios were obtained by simulation, as shown in Figure 10. Section S1 is 10cm away from the bottom stream mouth, and it can be clearly seen that the curves are distributed with single peak. When the shunt ratio increases to 40%, the decline rate of oil phase volume fraction slows down. When the shunt ratio increases to 50%, the oil phase volume fraction at the section will not decrease significantly with the positive value of the shunt ratio, which means that the oil phase volume fraction at the bottom flow port will not decrease any more.

![Figure 10. Oil phase volume fraction curve at S1 section at different shunt ratios](image)

The comparison diagram of the separation efficiency and pressure drop curves of the hydrocyclone with different shunt ratios was obtained by simulation, as shown in Figure 11. It can be seen that the oil phase separation effect and the pressure drop of the bottom flow port increase gradually with the increase of the shunt ratio, while the pressure drop of the secondary overflow port decreases gradually. When the
shunt ratio increases to 50%, the separation efficiency curve tends to be flat, at this point, the overflow shunt ratio increases the separation efficiency without significant change. The increase rate of the pressure loss at the bottom flow orifice increased sharply when the overflow shunt ratio increased to 50%, while the decrease rate of the pressure loss at the secondary overflow orifice slowed down when the overflow shunt ratio increased to 45%.

![Figure 11. Separation efficiency and pressure drop curves at different shunt ratios](image)

6. Experiment

6.1. Experimental process and technology

The test process is shown in Figure 12. After the gas is compressed by the air compressor, it enters the air tank for backup, and the control valve is opened to let it enter the static mixture. The oil pump pumps the oil storage tank through the valve control into the static mixer. The water from the screw is pumped into the static mixer. Gas, oil, and water are fully mixed in a static mixer and then injected into the device by double tangential inlet. The test will be conducted after the system is stabilised. The liquid flowmeter, gas flowmeter and pressure gauge measure the oil, gas and water before they enter the static mixer. After the separation, the bottom flow and the secondary overflow port are sampled, and the oil content is measured. The liquid and gas from the primary overflow port enters the recovery tank and are discharged through the gas flowmeter.

![Figure 12. Test flowchart](image)

The fluid volume of the cyclone was controlled at 19, 21, 23, 25 and 27 m$^3$/h by adjusting the valves connected with the gas-phase overflow pipe, the oil-phase overflow pipe and the bottom flow pipe. The cyclone shunt ratio was controlled. The total shunt ratios of the experiment were 35%, 40%, 45%, 50% and 55%.
6.2. Analysis of experimental results

Five groups were sampled under each operation parameter, and the oil concentration of the inlet, bottom flow and overflow sample was measured by an oil content analyser to reduce the adverse effect of operation error on the accuracy of experimental results. The average value of five groups of sample liquids was taken as the final oil concentration result, and the following equation [13] was substituted to calculate the separation efficiency:

\[
E = \frac{M_u}{M_i} = 1 - (1 - F) \frac{C_d}{C_i}
\]  

Where \(C_d\) is the oil concentration in the bottom flow port, mg/L; and \(C_i\) is the concentration of oil in the inlet, mg/L.

The inlet volumes are 19, 21, 23, 25 and 27 m³/h. The comparison curves of experimental and simulation efficiencies of the cyclone are shown in Figure 13. The experimental values of gas- and oil-phase separation efficiencies fit well with the simulated values. The fitting degree \(R^2\) of gas-phase separation efficiency is 0.92, and that of oil-phase separation efficiency is 0.94. The results show that with the gradual increase in treatment capacity, the experimental value of cyclone separation efficiency increases, decreases and reaches the maximum efficiency when the treatment capacity is 23 m³/h. The comprehensive analysis of the experimental and simulation results shows that the optimum treatment capacity of the cyclone structure is 23 m³/h, the optimum gas-phase separation efficiency is 92.4% and the oil-phase separation efficiency is 94%.

![Figure 13. Effect of flow on separation efficiency](image1)

![Figure 14. Effect of shunt ratio on oil-phase separation efficiency](image2)
7. Conclusion
(1) The numerical simulation results show that when the treatment capacity changes within the range of 19–27 m³/h, the gas- and oil-phase separation efficiencies firstly increase and then tend to be flat with the gradual increase in the treatment capacity; they decrease when the treatment capacity increases to 25 m³/h. During the experiment, with an increase in processing capacity, the two-phase separation efficiency shows a trend of firstly rising and then decreasing. The maximum separation efficiency is reached when the treatment capacity is 23 m³/h. Further increase of the treatment capacity will reduce the separation efficiency.

(2) The simulation shows that the separation efficiency is the highest when the total shunt ratio is 50%, the secondary shunt ratio is 35% and all other parameters are the same. The experimental results show that the gas- and oil-phase separation efficiencies increase firstly and then decrease with an increase in the total shunt ratio. The separation efficiency is the highest when the total shunt ratio is 50%. The experimental values are in good agreement with the simulated values.

(3) With an increase in processing capacity, the pressure drop at each outlet of the cyclone shows a trend of increasing gradually. With an increase in shunt ratio, the pressure drop at the bottom flow port increases gradually, whereas the pressure loss at the secondary overflow port decreases gradually.

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