INTRODUCTION

As oil production continues in oil fields, the water content in the produced liquid increases year by year, and some ultra-high water-bearing wells may face the risk of abandonment. The development of new oil displacement technology is put forward constantly. Recently, the feasibility of large-scale use of polymers in oil field development is determined.\textsuperscript{1-3} For polymer flooding technology, the viscosity characteristics of solution with high molecular weight polymers decrease the

Abstract

Polymer flooding technology is widely used to enhance the oil recovery, but it increases the viscosity of the produced liquid, making the subsequent water treatment more challenging. Application of polymers impacts separation performance of hydrocyclone, which is an important equipment of produced liquid preseparation and sewage treatment in oil fields. In this work, the effect of polymer solution concentrations on the separation performance of hydrocyclone was studied by using sensitivity analysis. The sensitivity was calculated by numerical simulation, and the influence of polymer concentration on velocity field, pressure field, oil volume fraction, and separation efficiency of hydrocyclone was evaluated. The prototype was processed according to the similarity principle of fluid mechanics, and the relevant laboratory tests were carried out to verify the accuracy of simulation results. Within the tested range (100-1000 mg/L), the increase of polymer solution concentrations caused adverse impacts on the velocity field, pressure field, and oil volume fraction of the hydrocyclone. When the concentrations of polymer solution reached 800 mg/L, the separation efficiency was reduced to less than 60%. The sensitivity sequence obtained by calculation is as follows: underflow outlet pressure drop > overflow outlet pressure drop > axial velocity > radial velocity > tangential velocity > pressure drop ratio. The change of pressure drop at underflow and overflow outlets was the primary cause for poor separation performance of hydrocyclone. The work can be used to guide the design and application of hydrocyclone for efficient treatment of polymer-containing treatment liquid.

KEYWORDS

hydrocyclone, laboratory tests, numerical simulation, polymer, sensitivity analysis, separation performance
permeability of water phase in rock formation and improve the wave coefficient of water phase. Meanwhile, the oil-water viscosity ratio is reduced. This technology also reduces the water content in the produced liquid and contributes to the enhanced oil recovery.\(^4\)\(^5\) As a type of efficient separation device, hydrocyclone is widely used in oil fields for preseparation of produced liquid and treatment of oily wastewater, and it can also be applied in underground mines.\(^6\)\(^8\) However, the viscosity characteristics of polymer solution can impact the internal flow field of hydrocyclone, resulting in poor separation performance.\(^9\)

In recent years, in order to improve the separation ability of hydrocyclone, the structure and flow field of hydrocyclone were studied. Xu\(^10\) investigated the influence of produced liquid viscosity on a three-phase hydrocyclone by combining numerical simulation with test and analyzed the impacts of viscosity on velocity field, pressure field, and separation efficiency of hydrocyclone. Liu\(^11\) designed a magnetic hydrocyclone. Through the interaction of centrifugal field and magnetic field, the centrifugal force and magnetic force were superimposed, which increased the separation force and avoided the breakage of oil droplets due to excessive velocity in the process of hydrocyclone. Liu\(^12\) designed a new type of double-cone air-sparged hydrocyclone to improve the ability of hydrocyclone to treat the produced liquid after polymer flooding, and the experimental results showed that the new hydrocyclone has better separation effect than gravity settling, conventional hydrocyclones, and flotation. However, these studies all lacked quantitative analysis on the flow field of hydrocyclone. The flow field is an effective index to evaluate the separation performance of hydrocyclone because it uses the centrifugal force generated by the flow field characteristics to achieve medium separation.\(^13\)\(^14\)

Sensitivity analysis is a method to study and analyze the sensitivity of the state or output changes of a system (or model) to the changes of system parameters or surrounding conditions. Sensitivity analysis is often used in method optimization to assess the stability of the optimal solution when the original data are inaccurate or changed.\(^15\)\(^16\) Sensitivity analysis is a fundamental element of any application analysis. This method has been successfully applied in various applications, and it can also determine which parameters have great influence on the system or model.\(^17\)

In this study, the sensitivity analysis method was applied to obtain the specific numerical value and size order of the influence of polymer solution concentrations on the flow field of hydrocyclone. Six important design functions of flow field were selected for sensitivity analysis. The impacts of polymer solution concentrations on the separation performance of hydrocyclone were studied by a numerical simulation method, and the sensitivity was calculated by using the simulation results. The relevant laboratory tests were carried out to verify the numerical simulation data. Rheological experiments, including the preparation of polymer solutions with different concentrations, rheological properties measurement, and data fitting, were performed to obtain the numerical simulation parameters of polymer solutions with different concentrations. The velocity field, pressure field, oil volume fraction, and separation efficiency were analyzed, and the sensitivity calculation was completed. According to sensitivity calculation, the order of factors for the poor separation performance caused by the change of polymer solution concentrations was determined.

## 2  METHODS

### 2.1  Flow field research based on sensitivity analysis

Based on the sensitivity analysis, the effect of polymer solution concentration on the flow field of hydrocyclone was studied. The research process includes sensitivity analysis scheme design, numerical simulation calculation, and sensitivity calculation. The specific research roadmap is shown in Figure 1.

The sensitivity of the function to the variable is caused by the small change of the function to the variable at a certain point, that is, the partial derivative of the function to the variable,\(^18\) as shown in Equation (1):

\[
S_{ij} = \frac{\partial \phi_i(x)}{\partial x_j} \mid x = x_k, i = 1, 2, \ldots, m; j = 1, 2, \ldots n.
\]

where, \(S_{ij}\) — Sensitivity;

\(\phi_i(x)\) — Design function;

\(x_j\) — Variable.

The positive and negative of \(S_{ij}\) represents the monotonicity of \(\phi_i(x)\). The viscosity of polymer solution was characterized by concentration, that is, \(x_j\) was the concentration of polymer solution \(\mu_i\). Hydrocyclone relies on centrifugal force to separate media with different densities, and centrifugal force comes from velocity. In the process of medium separation, the tangential velocity \(V_t\) is the premise of centrifugal force, the axial velocity \(V_a\) determines the separation time, and the radial velocity \(V_r\) realizes the medium exchange. There are no moving parts in the hydrocyclone, and the velocity comes from the pressure drop. Therefore, the pressure drop of overflow outlet \((P_o)\) and underflow outlet \((P_d)\) and the relationship between them, pressure drop ratio \((P_b)\), are also important parameters of hydrocyclone flow field. Therefore, six design functions of velocity field and pressure field of hydrocyclone were drawn up as follows: tangential velocity \(V_t\), axial velocity \(V_a\), radial velocity \(V_r\), overflow outlet pressure drop \((P_o)\), underflow outlet pressure drop \((P_d)\), and pressure drop ratio \((P_b)\), without considering monotonicity.
According to the selection of reasonable amount of polymer flooding in Daqing Oilfield, the actual engineering dosage range of polymer concentration is 100-1000 mg/L, which was used as the reference concentration for preparing polymer solution. The sensitivity was calculated by taking the polymer concentration of 200-400 mg/L, 400-600 mg/L, 600-800 mg/L, and 800-1000 mg/L for \( \Delta \mu_1 \), \( \Delta \mu_2 \), \( \Delta \mu_3 \), and \( \Delta \mu_4 \), respectively. Increase of the polymer solution with concentration of 100 mg/L as reference concentration, and carry out dimensionless treatment on the sensitivity calculation results, as shown in Figure 2. The function value was calculated by numerical simulation.

### 2.2 | Numerical simulation parameters determination

#### 2.2.1 | Selection of hydrocyclone

A kind of axial spiral flow channel diversion hydrocyclone was selected and studied. Its structure is mainly composed of spiral flow channel, swirling chamber, cone segment, and inverted cone. The inverted cone of the hydrocyclone can play the role of pressurization and acceleration, greatly reducing the axial size of the traditional hydrocyclone and reducing the floor area. The oil-water mixture enters the hydrocyclone from the inlet tube and forms a strong swirl in the swirling chamber and cone section after being pressurized and accelerated through the spiral flow channel. Due to the density difference between oil and water, under the action of centrifugal force, heavy phase water migrates to the side wall and is discharged from the underflow outlet. The light phase oil migrates to the central axis of the hydrocyclone and is discharged from the overflow outlet to realize separation. The plane S is 18 mm below the spiral flow channel, which was used as the research plane of the internal flow field of the hydrocyclone.
hydrocyclone, as shown in Figure 3. The specific structural dimensions are shown in Table 1.

2.2.2 | Grid generation and independence verification

The inlet tube of the hydrocyclone was omitted in the process of simplifying the fluid domain, and the inlet tube was replaced by the axial flow inlet. Because the axial spiral flow channel diversion hydrocyclone is different from the traditional hydrocyclone, it realizes pressurization and acceleration of the treated liquid through the pressurization boss and spiral flow channel. Meanwhile, the size of overflow tube was shortened. Gambit software was used to mesh the simulation domain of hydrocyclone. In order to ensure the accuracy of the simulation calculation, the fluid domain of the hydrocyclone was divided into five grid levels by hexahedron mesh method Standard1-Standard5 (146 361, 213 126, 306 243, 401 344, 491 457). The underflow outlet pressure drop of hydrocyclone and the volume fraction of oil phase at the overflow outlet were monitored simultaneously, and the grid independence test was carried out.

![Structure diagram of hydrocyclone](image)

**FIGURE 3** Structure diagram of hydrocyclone

As shown in Figure 4, the curve of the pressure drop at the underflow outlet of the hydrocyclone and the oil phase volume fraction of the overflow outlet with the grid level was shown. With the increase of the number of grids, they all show an increasing trend. When the grid level reaches Standard 4, the numerical value basically does not change, which indicates that the number of grids has no influence on the simulation results. Therefore, the standard 4 grid level was selected for the next numerical simulation. As shown in Figure 5, the simplified model and meshing results of hydrocyclone simulation domain were presented.

2.2.3 | Numerical simulation parameter setting

Numerical simulation was carried out by using ANSYS Fluent software. The power law fluid model suitable for polymer solution was used to simulate the oil-water separation of the hydrocyclone. Reynolds stress model (RSM) was selected as turbulence calculation model. Considering the coupling effect between oil and water, the multiphase mixture model (Mixture) was used in the simulation. The continuous phase was set as water phase with density of 998.2 kg/m³, and discrete phase was set as oil phase with density of 889 kg/m³ and oil content of 2%. The inlet adopted velocity inlet (Velocity). According to the treatment capacity of 4 m³/h of hydrocyclone, the inlet velocity was 0.6 m/s. The overflow and underflow outlets were set as free outlets (Outflow), the overflow outlet split ratio was set to 20%, and the underflow outlet split ratio was set to 80%. Considering the influence of gravity on separation, the acceleration of gravity was set to 9.81 m/s². The same boundary conditions and grid models were used in all numerical simulations except for the concentration parameter setting of polymer solution.

The rheological parameters of polymer solution were measured by rheological experiment, which provided data support for numerical simulation. The experiment includes the preparation of polymer solutions with different concentrations and

| Structure                        | Size/ mm |
|----------------------------------|----------|
| Length of pressurization boss L₁ | 30       |
| Length of spiral flow channel L₂ | 57       |
| Length of swirling chamber L₃   | 70       |
| Length of cone segment L₄       | 239      |
| Length of inverted cone L₅      | 150      |
| Length of underflow pipe L₆     | 50       |
| Diameter of swirling chamber D  | 50       |
| Diameter of overflow pipe Dₒ    | 8        |
| Diameter of underflow pipe Dₜ   | 25       |

**TABLE 1** Specification of the hydrocyclone
the measurement of rheological parameters. In order to eliminate the influence of oil on the rheological properties of polymer solution, 2% oil was added to all concentration polymer solutions during the rheological experiment, which was consistent with the condition of 2% oil in numerical simulation and laboratory test. The rheological properties of polymer solutions with different concentrations were measured by Malvern rheometer at 20°C. The viscosity and shear stress of polymer solutions with different concentrations at different shear rates can be obtained by rheological measurement. Polymer solution belongs to pseudoplastic fluid, and its rheological properties conform to empirical power law equation, as shown in Equation (2):

\[ \tau = K\dot{\gamma}^n \]  

(2)

where, \( K \)—Consistency coefficient; \( n \)—Flow index.

According to the power law equation, the shear stress and shear rate of polymer solutions with different concentrations were fitted, and the fitting curve was shown in Figure 6. The power law equations of polymer solutions with different concentrations were obtained by curve fitting, as shown in Table 2. Through the fitting degree \( R^2 \), we can see the correctness of using the power law equation. The consistency coefficient and flow index in the power law equation of polymer solution with different concentrations were used for numerical simulation.

### 2.3 Simulation reliability verification

In order to ensure the reliability of the numerical simulation, relevant indoor tests were carried out to verify the simulation results. The flow chart of laboratory test is shown in Figure 7. The mixing pump can realize the mixing during the preparation of polymer solution with different concentrations in the storage tank. After the solution preparation was completed, the polymer solution was pumped...
by the screw pump and the test oil was pumped by the oil pump. The polymer solution and oil were mixed into the hydrocyclone by a static mixer. The treatment capacity of the hydrocyclone was 4 m³/h controlled by inlet valve, and the split ratio of the overflow outlet was controlled at 20%, which was consistent with the simulation value. Samples were taken at the underflow outlet of hydrocyclone in each group. The method of carbon tetrachloride extraction was used to measure the oil concentration by infrared spectrophotometer, and the efficiency was calculated by the oil concentration.

As shown in Figure 8, with the increase of overflow split ratio of hydrocyclone, the pressure drop of overflow outlet decreased gradually. The simulated value was different from the experimental value, and the fitting degree $R^2$ is 0.9723 by polynomial fitting. The reliability of the numerical simulation results was proved by comparing the simulated and experimental values of the pressure drop at the overflow outlet and the oil concentration at the underflow outlet of the hydrocyclone.

### Table 2

| Concentration of polymer solution | Rheological equation |
|-----------------------------------|----------------------|
| 100 mg/L                          | $\tau = 0.0015 \gamma^{1.0124}$ |
| 200 mg/L                          | $\tau = 0.0022 \gamma^{0.9931}$ |
| 400 mg/L                          | $\tau = 0.0047 \gamma^{0.9054}$ |
| 600 mg/L                          | $\tau = 0.0089 \gamma^{0.8411}$ |
| 800 mg/L                          | $\tau = 0.00131 \gamma^{0.8247}$ |
| 1000 mg/L                         | $\tau = 0.00192 \gamma^{0.7874}$ |

### Figure 6

Fitting curves of shear stress and shear rate of polymer solution with different concentration.

### 3 | RESULTS AND DISCUSSION

#### 3.1 | Analysis of numerical simulation results

**3.1.1 | Velocity field**

As shown in Figure 10, the tangential velocity of different concentrations of polymer solution showed a uniform trend and distributes symmetrically along the central axis. The minus sign only represents the direction of velocity. There was a maximum tangential velocity in the range of 20-25 mm from the central axis, as the internal quasi-strong vortex and the external quasi-free vortex dividing line. The tangential velocity rose with the increase of radius in the quasi-strong vortex, but decreased in the quasi-free vortex until the tangential velocity at the side wall was zero. When the concentration of polymer solution increased from 100 mg/L to 1000 mg/L, the maximum tangential velocity of S plane decreased from 2.81 m/s to 2.54 m/s.
1. Axial velocity

With the same tangential velocity, the increase of polymer solution concentration did not change the overall trend of axial velocity, and it was symmetrically distributed along the central axis, as shown in Figure 11. The minus sign only represents the direction of velocity. Along the radial direction, two zero axial velocity points were noticed except the side wall, which was the position of the zero axial velocity envelope surface of the hydrocyclone. The inside of the envelope surface was internal swirl, and the outside was external swirl. The axial migration of internal and external swirl was accompanied by radial medium exchange under centrifugal force. The light phase of the external swirling flow will pass through the zero axial velocity envelope, enter the internal swirling flow and be discharged from the overflow outlet. The heavy phase of the internal swirling flow will pass through the zero axial velocity envelope surface and enter into the external swirling flow and be discharged from the underflow outlet. This is also the main reason for the radial velocity. On the inner and outer sides of the zero axial velocity envelope, the axial velocity rose with the increase of the polymer solution concentrations. When the polymer solution increased from 100 mg/L to 1000 mg/L, the
maximum axial velocity difference between the inner and outer sides of the zero axial velocity envelope was 0.088 m/s and 0.054 m/s, respectively.

1. Radial velocity

As shown in Figure 12, with the same tangential velocity and axial velocity, the change of polymer solution concentration did not change the overall distribution trend of radial velocity. The radial velocity near the central axis was larger and the radial velocity at the side wall was smaller, which is due to the separation of media. The light phase oil phase migrates to the axis under the action of centrifugal force, while the heavy phase water phase migrates to the side wall. The water phase is continuous and the radial velocity is not obvious. The dispersed phase is the oil phase with 2% content, so the radial velocity in the swirl chamber is mainly reflected in the speed of oil gathering toward the central axis, and the radial velocity near the central axis is larger. The higher the concentrations of polymer solution, the smaller the velocity near the axis, which is not conducive to the accumulation and separation of oil phase. When the concentration of polymer
solution increased from 100 mg/L to 1000 mg/L, the radial velocity decreased from 0.3 m/s to 0.25 m/s.

3.1.2 Pressure field

With the increase of polymer solution concentrations, the pressure drops at overflow and underflow outlets decreased, as shown in Figure 13. Pressure drop refers to the pressure drop at the inlet of hydrocyclone minus the pressure value at the corresponding position, which is also an important parameter to evaluate the separation performance of hydrocyclone. The total pressure is the sum of static pressure and dynamic pressure. When discussing the pressure drop of hydrocyclone, the hydrocyclone is regarded as a whole and only the static pressure of hydrocyclone is concerned.

As shown in Figure 14, with the increase of polymer solution concentration, the pressure drop ratio increases slightly. The pressure drop ratio is the ratio of the pressure drop at the overflow outlet and the pressure drop at the underflow outlet. The pressure drop ratio not only reflects the pressure drop of hydrocyclone, but also indicates the
relationship between the pressure drop of overflow outlet and that of underflow outlet. The pressure drop ratio usually changes with different input parameters, which is often nonlinear. Pressure drop ratio is another important parameter in the study of hydrocyclone, which is of great significance to the industrial applicability of hydrocyclone. Taking pressure drop ratio and pressure drop as design function, with the increase of polymer solution concentrations, a single factor of overflow outlet or underflow outlet of hydrocyclone is more affected, or the relationship between them is more affected.

3.1.3 | Volume fraction of oil

As shown in Figure 15, when the polymer solution concentration increased, the oil phase gathering at the central axis of hydrocyclone decreased. The brightness of the bright line in the center of the hydrocyclone represents the volume fraction of the oil phase. The higher the brightness of the bright line is, the higher the volume fraction of oil collected at the central axis of the hydrocyclone is. The same trend was observed for oil volume fraction distribution curves on S plane of hydrocyclone (Figure 16). With the increasing concentrations
of polymer solution, the volume fraction of oil phase converging on the central axis of the hydrocyclone was reduced gradually.

3.1.4 | Separation efficiency

The efficiency was calculated according to the efficiency formula, as shown in Equation (3) and Equation (4):

\[ E_j = 1 - \frac{C_d}{C_i} \]  

\[ E_m = 1 - (1 - F) \frac{C_d}{C_i} \]  

where,  
- \( E_j \)—Simplified efficiency (%);  
- \( E_m \)—Mass efficiency (%);  
- \( C_i \)—Oil concentration at inlet (%);  
- \( C_d \)—Oil concentration at underflow outlet (%);  
- \( F \)—Overflow outlet split ratio (%);

As shown in Figure 17, with the increase of polymer solution concentrations, the separation efficiency of hydrocyclone decreases linearly, and the R\(^2\) of linear fitting degree is 0.9887.
When the concentration of polymer solution reached 800 mg/L and 1000 mg/L, the separation efficiency was below 60%. Here, the mass efficiency formula was used to calculate the efficiency.

3.1.5 | Separation performance evaluation of hydrocyclone

Alteration of the velocity field, pressure field, oil volume fraction, and separation efficiency by the increase of polymer solution concentrations suggest the separation performance of hydrocyclone. As the polymer concentration increased, the tangential velocity decreased, axial velocity increased, radial velocity decreased, and pressure drop decreased. The decrease of tangential velocity reduced the centrifugal force of medium separation, and the increase of axial velocity reduced the separation time of medium in the hydrocyclone. Pressure drop was the source of separation power of hydrocyclone, so the decrease of pressure drop reduced the separation power of hydrocyclone. Therefore, the separation efficiency
of hydrocyclone was obviously reduced. The decrease of radial velocity was not conducive to the convergence of oil phase to the center axis of the hydrocyclone, and the low volume fraction of oil phase at the central axis of hydrocyclone was not conducive to the separation of oil phase from overflow outlet. The results showed that the increase of polymer concentrations had adverse effect on the velocity field, pressure field, oil volume fraction, and separation efficiency of hydrocyclone, resulting in its poor separation performance.

3.2 Sensitivity analysis of design function

Through sensitivity calculation, the sensitivity of the six velocity and pressure field functions in the hydrocyclone to the concentration change of polymer solution was obtained, as shown in Figure 18. The sensitivity of the pressure drop at the overflow outlet and underflow outlet to the change of polymer solution concentration remained in the same level, and the other four design functions were lower.

In order to determine the order of sensitivity of six design functions to the change of polymer solution concentration, the sensitivity of four research intervals of each design function was averaged to evaluate the overall sensitivities, as shown in Figure 19. The sensitivity order of the functions of velocity field and pressure field with the change of polymer solution concentration was obtained as follows:

\[
|S_{\phi_1}|_{P_u} > |S_{\phi_2}|_{P_o} > |S_{\phi_3}|_{V_r} > |S_{\phi_4}|_{V_t} > |S_{\phi_5}|_{V_r} > |S_{\phi_6}|_{P_o}.\]

This suggests the main reason why the separation performance of hydrocyclone decreased with the increasing polymer solution concentrations was the change of pressure drop at underflow and overflow outlets.

4 CONCLUSIONS

In this paper, the numerical simulation method was used to analyze the flow field of hydrocyclone and calculate the sensitivity at a wide range of polymer concentrations, and the experimental verification was carried out. The following conclusions were obtained.

1. The numerical simulation results showed that the increase of polymer solution concentrations had adverse effect on the velocity field, pressure field, and oil volume fraction of hydrocyclone. When the concentration of polymer solution was no lower than 800mg/L, the separation efficiency of hydrocyclone is below 60%.

2. Via sensitivity calculation, the sensitivity order of design function is as follows: underflow outlet pressure drop > overflow outlet pressure drop > axial velocity > radial velocity > tangential velocity > pressure drop ratio. The main cause for the poor separation performance of hydrocyclone at high polymer concentrations was the decrease of pressure drop at underflow and overflow outlets, followed by the change of velocity field.

3. The results of sensitivity analysis provide guidance for the design and application of hydrocyclone. To separate polymer-containing treatment liquid, the hydrocyclone with larger pressure drop of underflow outlet and overflow outlet should be considered. When the structure of the hydrocyclone is designed and optimized, the pressure...
drop of underflow outlet and overflow outlet should be appropriately increased.

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