Experimental and numerical simulation study on the flow characteristics and optimization of structural parameters of displacement agent in partial pressure tools

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1 | INTRODUCTION

During the exploitation of Daqing oilfield, polymer flooding technology has been used to effectively improve the oil recovery.\(^1\)\(^,\)\(^3\) At present, with the increasing difficulty of exploitation of the Daqing oilfield, the heterogeneity of oil layers is becoming increasingly challenging to manage. In the process of polymer flooding using traditional injection methods, most of the polymer solution enters the oil layers with higher permeability,\(^4\) resulting in poor production of medium- and low-permeability oil layers, and thus failing to achieve the ideal flooding effect.\(^5\) In order to solve this problem, Daqing oilfield has proposed partial pressure injection technology,\(^6\)\(^,\)\(^7\) in which partial pressure tools are used to reduce the injection pressure of the polymer solution during oil displacement in high-permeability reservoirs, the injection amount is controlled, and layered injection allocation is carried out to ensure the oil displacement efficiency of the polymer solution in the high-permeability oil layer, and increase the injection amount of polymer solution into the low-permeability oil layer, so that the polymer solution enters the low-permeability oil layer more for oil displacement, and improve the overall oil recovery.

In order to control the injection amount of the displacement agent in the high-permeability reservoir, the previous research used profile control to block the pore channels of the high-permeability reservoir and control the injection amount of the displacement agent in the high-permeability reservoir to solve the problem of reservoir heterogeneity.

Previous studies have shown that injecting gel into formation can be used as an effective profile control method. According to the geological characteristics of low-permeability reservoirs in Daqing oilfield, Zhou et al\(^8\) optimized the formulation of a cross-linked polymer gel system for deep profile control in this block through orthogonal experiments. The results show that when the injection amount reaches 0.6 PV, the optimal profile control system can effectively block high-permeability cores, and has little influence on low-permeability cores. Zhao et al\(^9\) analyzed the mechanism of air foam flooding and showed that air foam flooding can improve the oil displacement performance after water flooding. Li et al\(^10\) conducted oil displacement experiments of a foam system on a reservoir in porous media model and sandbags. The experimental results show that the foam system enhances the plugging effect of the high-permeability layer and the medium-permeability layer, while the flow restriction in the low-permeability layer is very small.

In addition to using profile control method to control the injection amount of displacement agent in high-permeability oil layer, relevant research shows that the injection amount can be controlled by using flow control device in the process of oil field production, because the pressure of solution (Bernoulli’s law) changes when the fluid flows through the flow control device, thus controlling the injection amount of fluid.\(^16\)\(^,\)\(^17\) In the oil industry, tools of adjusting fluid pressure to control fluid flow effect are mostly applied to drilling technology,\(^18\)\(^-\)\(^22\) oil and gas exploitation,\(^23\)\(^,\)\(^24\) offshore work,\(^25\)\(^-\)\(^27\) and oil and gas transportation.\(^28\)\(^-\)\(^31\) For downhole operation and production, some scholars have studied a flow control device which can realize the completion of horizontal wells, prevent early water and gas breakthrough, and improve the oil recovery. Augustine et al\(^32\) applied inflow control devices in the North Sea area of England, and undertook a comprehensive analysis on the selection process of control devices, completion and...
reservoir, completion operation summary, production results, and predictions. The results show that the device improves the overall production efficiency. Henriksen et al.\textsuperscript{33} studied the application of inflow control devices (ICDs) in the Troll Oil sub-sea field development. Computer modeling and production experience have proved that ICDs enable each well to achieve higher oil recovery. Coronado et al.\textsuperscript{34} put forward a new concept of hybrid design development, which uses the best characteristics of restriction and friction design to improve the erosion resistance and the ability to effectively balance inflow of ICDs. Least et al.\textsuperscript{35} proposed an independent inflow control device (AICDs) and conducted laboratory experiments. The results show that the AICD can utilize 61\% more oil and gas resources than ICDs in completion design, bringing significant benefits to production enterprises and enterprises participating in completion design and modeling of new wells. Garcia et al.\textsuperscript{36} proposed a passive inflow control device (PICD) and quantified it through a complete integrated reservoir simulator to determine the potential application of the PICD in horizontal wells, and the best completion strategy suitable for specific reservoir conditions.

Profile control is used to solve the problem of reservoir heterogeneity in the process of oil displacement. Although it can effectively adjust the injection amount of the displacement agent in high-permeability reservoirs and improve the oil displacement effect, most profile control agents are chemical substances, which will pollute the formation and produced water during the injection process. Although the flow control device used can adjust the injection amount, it is only aimed at the completion engineering of horizontal wells. Therefore, it is of great significance to study a partial pressure tool for adjusting the injection amount of displacement agents in high-permeability reservoirs which cannot change the formation structure and not pollute the formation. Huang et al.\textsuperscript{37} established the rheological equation of the polymer solution in the partial pressure tool and the transition velocity equation for the polymer solution based on the concept of stability factor. However, this study only studies the effect of partial pressure tools from a theoretical point of view and lacks the ability to verify the effectiveness of tools and improve the oil recovery of heterogeneous reservoirs through experiments.

In this paper, the physical model of the partial pressure tool is established, and unstructured grid division is carried out on the model. Then, finite element analysis is carried out on the flow process of the polymer solution in the partial pressure tool, and the influence of the partial pressure tool on the velocity, pressure, viscosity, and strain rate of the polymer solution is studied. At the same time, the accuracy of the numerical simulation results is verified by laboratory experiments under different flow rates and polymer solution concentrations. Finally, according to the effect of the partial pressure tool on the polymer solution, under the condition that a large pressure drop can be generated and the viscosity loss rate of the solution is small, the optimal structural parameters of the partial pressure tool are selected through orthogonal experiments and variance analysis.

2 | LABORATORY EXPERIMENTAL STUDY ON THE FLOW OF POLYMER SOLUTION IN THE PARTIAL PRESSURE TOOL

2.1 | Experimental model

Using the principle of the labyrinth seal,\textsuperscript{38-40} a partial pressure tool with a throttling groove structure was developed. Figure 1 shows a three-dimensional structure diagram of the partial pressure tool. When the polymer solution flows
through the throttling units of each throttling groove, the flow area changes once from small to large, and the flow and flow field distribution also change once accordingly. Since polymer solution can generate a small throttling pressure difference under one throttling unit, when a plurality of such units are combined together, the final accumulated pressure drop meets the throttling pressure difference, thus achieving the purpose of controlling the injection amount.

The outer surface of the partial pressure tool is a cylinder, and it forms a flow channel with an internal throttling groove. Figure 2 shows a two-dimensional cross section of the flow channel. In order to reduce the viscosity loss of the polymer solution in the flow process, the design of the throttling groove avoids having a sharp structure in the place where the solution flows, appropriately increases the flow area, adopts arc transition and other methods in the place where the arc and the straight line are not tangent, ensures that the wall surface of the throttling groove runner is all smooth curved surface, and reduces the viscosity loss. In order to reduce the influence of the port effect and make the flow occur in a fully developed section, an annular flow space of 10 mm is lengthened at each end of the throttling groove. In the model, the inner diameter Ro of the outer cylinder is 19 mm, the minimum distance between the throttling groove and the outer cylinder is 0.5 mm, the convex circle radius R1 is 3 mm, and the concave circle radius R2 is 1 mm.

2.2 Experimental process

The pressure drop and viscosity loss rate of the polymer solution with different concentrations flowing through the partial pressure tool under different flow rates were experimentally studied in the laboratory. The experimental materials are shown in Table 1, and the experimental process chart is shown in Figure 3.

The polymer used to prepare the polymer solution is partially hydrolyzed polyacrylamide (HPAM), with a relative molecular weight of $1600 \times 10^4$ and a degree of hydrolysis of about 26%. In order to truly simulate the polymer flooding conditions in Daqing Oilfield, the polymer solution is prepared by diluting the solution with injected brine, which is taken from No. 1 Oil Production Plant of Daqing Oilfield and must be filtered by a filter membrane before use. The composition of the injected brine is shown in Table 2. The polymer solutions are diluted to a concentration of 1000, 1500, and 2000 mg/L, respectively, by using injected brine.

The temperature was kept at 45°C during the experiment. Before the experiment, we checked whether all devices were tightly connected. After the check, polymer solutions with concentrations of 1000, 1500, and 2000 mg/L were added into the liquid supply tank in batches, the valve was opened and the liquid supply pump started, respectively, to control the flow range to 5-100 m$^3$/d, and to allow the solution to flow back to the recovery tank after passing through the partial pressure tool (the structural parameters are consistent with those in the model). In this process, when the readings of the flowmeter and pressure gauge were stable, we recorded the readings of the pressure gauge before and after flow occurred through the partial pressure tool, sampling the polymer solution before and after flowing through the partial pressure tool, measuring the viscosity of the solution with a rheometer, and closing the valve after the experiment was completed. We used the following formulas for calculating the pressure drop and viscosity loss rate of solutions produced by partial pressure tool:

$$\Delta p = p_1 - p_2 \quad (1)$$

$$\varphi = \left( \frac{\mu_1 - \mu_2}{\mu_1} \right) \times 100\% \quad (2)$$

where $\Delta p$ is the pressure drop, Pa; $p_1$ is the solution pressure before flowing through the partial pressure tool, Pa; $p_2$ is the solution pressure after flowing through the partial pressure tool, Pa; $\varphi$ is the viscosity loss rate of the solution after flowing through the partial pressure tool, %; $\mu_1$ is the solution viscosity before flowing through the partial pressure tool, mPa·s; and $\mu_2$ is the viscosity of the solution flowing through the partial pressure tool, MPa·s.

In order to ensure the accuracy of the experiment and reduce the experimental error, the laboratory experiments at each concentration and each flow rate were repeated three times, and the final results were averaged.

![Figure 2](image-url) Two-dimensional cross section of the flow channel
In this paper, CFD was applied to calculate and solve the problem. The process was divided into several subregions in the discretization of the calculation area, and grids were generated according to the nodes in each region during the discretization. Then, the control equation established according to the actual situation was discretized on the grid and converted into algebraic equations at each node. The discretization of the control equation is mainly the division of the grid. After the geometric model was established, the ICEM-CFD software was used to mesh the model of the partial pressure tool.

Through topological analysis of the three-dimensional geometric model of the polymer solution in the flow passage of the partial pressure tool, the calculation domain was divided into a plurality of blocks of divisible unit grids, and then, the grids with tetrahedral units were generated as a
whole; the unstructured tetrahedral units were adopted to divide the grids for the partial pressure tool with the arc throttling groove, so that the calculation amount could be reduced, and the calculation stability and accuracy could be obviously improved. In order to check grid independence, for the tool model, four grids with different grid numbers of 1.55, 2.16, 2.76, and 3.05 million were checked, the verification results are shown in Table 3. It was found that when the grid number was not <2.76 million, the result was no longer sensitive to the grid number. Therefore, 2.76 million was selected for simulation in this work. In order to accurately simulate the flow state of the polymer solution at the boundary when generating the overall grid of the model, boundary layer grids were set on the boundary of the outer cylinder and the throttling groove wall. The grid division of the partial pressure tool is shown in Figure 4.

### 3.2 Mathematical model

#### 3.2.1 Basic governing equations

According to the flow field characteristics of polymer flowing in throttling groove, appropriate equations and models were selected and reasonably simplified. In this numerical simulation, the thermodynamic process is not considered, and it is assumed that the physical quantity of the flow field in the throttling groove does not change with time, which is

| Number of grid | 1.55 million | 2.16 million | 2.76 million | 3.05 million |
|----------------|--------------|--------------|--------------|--------------|
| Pressure drop (MPa) | 1.51 | 1.67 | 1.82 | 1.83 |

**TABLE 3** Grid independence test
a constant incompressible flow. The influence of gravity is not considered. The basic control equations established were as follows:

Continuity equation:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0$$  \hspace{1cm} (3)

Momentum equation:

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho \varepsilon$$  \hspace{1cm} (4)

where \( p \) is the pressure on the fluid microelement, Pa; \( \tau_{ij} \) is the viscous stress tensor acting on the surface of the microelement due to molecular viscous action, N/m²; \( \varepsilon \) is hydrodynamic viscosity, MPa s; \( \rho \) is density, kg/m³.

### 3.2.2 Turbulence model

In order to study the flow characteristics of the polymer solution in specific tools, the RNG k-\( \varepsilon \) model was used in the numerical simulation. This model is a semi-empirical formula, which is mainly based on turbulence kinetic energy and diffusivity. In the model, \( \varepsilon = \frac{u}{\rho} \left( \frac{\partial u_i}{\partial x_i} \right) \left( \frac{\partial u_j}{\partial x_j} \right) \), \( k = \frac{1}{2} u_i u_j \), and turbulence viscosity is \( \mu_t = \frac{\rho C_k^2}{\varepsilon} \). The equations of \( k \) and \( \varepsilon \) are defined as:

$$\frac{\partial (\rho k u_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( a_k \mu_t \frac{\partial k}{\partial x_j} \right) + G_k - \rho \varepsilon$$  \hspace{1cm} (5)

$$\frac{\partial (\rho \varepsilon u_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( a_\varepsilon \mu_t \frac{\partial \varepsilon}{\partial x_j} \right) + C_{1\varepsilon} \frac{\varepsilon}{2} \frac{\varepsilon}{k} - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k}$$  \hspace{1cm} (6)

where \( k \) is the turbulence kinetic energy, J; \( \varepsilon \) is turbulent kinetic energy dissipation rate, %; \( \rho \) is density, kg/m³; \( G_k \) is the turbulent kinetic energy generation term due to the average velocity gradient, J; \( \mu_t \) is diffusion coefficient, MPa s; \( a_k \) and \( C_{1\varepsilon} \) are reference coefficient, dimensionless number.

\( \mu_t \) is calculated as follows:

$$\mu_t = \mu + \mu_i$$  \hspace{1cm} (7)

where \( \mu \) is hydrodynamic viscosity, MPa s; \( \mu_i \) is turbulent viscosity, MPa s.

\( a_k \) and \( a_\varepsilon \) in Equations 5 and 6 are calculated by the following formula:

$$\alpha = 1.3929, \alpha_o = 1.3929$$

where \( \alpha_o = 1.3929 \) is the apparent viscosity of the power-law fluid.

For polymer solutions, the constitutive equations of non-Newtonian power-law fluids are mostly adopted:

$$\tau = Ke^{T_e/T}(\dot{\gamma})^n = (Ke^{T_e/T}(\dot{\gamma})^{n-1})\dot{\gamma}$$  \hspace{1cm} (14)

The expression of the apparent viscosity of the power-law fluid was obtained as follows:

$$\eta = Ke^{T_e/T}(\dot{\gamma})^{n-1}$$  \hspace{1cm} (15)
The upper and lower limits of apparent viscosity can be set in Fluent, namely.

$$\eta_{\min} < Ke^{T_o/T}(\dot{\gamma})^{n-1} < \eta_{\max}$$  \hspace{1cm} (16)$$

where $K$ is the average viscosity coefficient (consistency coefficient) of the fluid, Pa s; $n$ is the non-Newtonian strength coefficient (power-law index) of the fluid, dimensionless number; $T_o$ is the reference temperature, °C; $\eta_{\min}$ and $\eta_{\max}$ are the lower limit and upper limit of the apparent viscosity of the power-law fluid, respectively, Pa s. If the apparent viscosity calculated according to the power-law fluid model exceeds the upper and lower limits of viscosity, the calculated viscosity values are replaced by the values of $\eta_{\min}$ and $\eta_{\max}$. For the power-law equation in the model, $T_o$ is set to 0°C, $\eta_{\min}$ is set to 0.01 Pa·s, $\eta_{\max}$ is set to 1 Pa·s, and $n$ and $K$ are related to the properties of the polymer solution.

### 3.3 Boundary conditions

Since the partial pressure tool is of a single inlet and a single outlet structure with a closed periphery, the inlet adopts a speed inlet and the inlet flow rate is a fixed value, and the inlet and outlet speed is converted according to the inlet flow rate:

$$u_{\text{lin}} = \frac{Q}{2A_{\text{lin}}}.$$  \hspace{1cm} (17)$$

Turbulent flow at the inlet is calculated using the turbulence intensity and hydraulic diameter:

$$I \equiv \frac{u'}{u_{\text{lin}}} \approx 0.16(\text{Re}_H)^{-1/8}$$  \hspace{1cm} (18)$$

$$D_H = \frac{4A_{\text{in}}}{C_{\text{in}}}$$  \hspace{1cm} (19)$$

where $u_{\text{lin}}$ is the fluid velocity perpendicular to the inlet boundary, m/s; $A_{\text{in}}$ is the cross-sectional area of the entrance, m$^2$; $Q$ is inlet flow, m$^3$/s; $u'$ is the inlet pulsation speed, m/s; $D_H$ is hydraulic diameter, m; and $C_{\text{in}}$ is wetted perimeter, m.

The outlet boundary is set as the pressure outlet, and the outlet pressure is 0 MPa.

The above k-ε model is only applicable to the turbulent central region. Near the wall, turbulence forms a boundary layer. Due to the lower Reynolds number in the boundary layer, the changes of turbulence kinetic energy and dissipation energy are more complex and are not suitable for determination by the differential transport equation.

The flow field at the solid wall boundary belongs to the boundary layer flow field. The wall function method can reduce the calculation amount and improve the simulation accuracy. The wall area consists of three sublayers: the viscous bottom layer, transition layer, and logarithmic law layer. Velocity and distance are expressed by two dimensionless parameters: $u^+$ and $y^+$, respectively:

$$u^+ = \frac{u}{u_*}$$  \hspace{1cm} (20)$$

$$y^+ = \frac{\Delta y \rho u_*}{\mu} = \frac{\Delta y}{u} \sqrt{\frac{T_w}{\rho}}$$  \hspace{1cm} (21)$$

where $u$ is the time average speed, m/s; $u_*$ is the wall friction number $(\tau/\rho)^{0.5}$, m/s; $T_w$ is the wall shear stress, Pa; and $\Delta y$ is the distance from the solution to the wall, m.

The steady numerical calculation method was selected. The finite volume method was used for discretization of the calculation area. The second-order upwind scheme was used for discretization of the equation convection term. The flow equation and turbulence equation were solved simultaneously. The pressure and velocity were solved by the SIMPLE (Semi-Implicit Method for Pressure Linked Equations) method, coupled with pressure and velocity. The algebraic equation was solved iteratively by the under relaxation method. The pressure difference scheme was PRESTO (Pressure Staggering Option). The convergence criteria for residual values of variables were all $10^{-6}$.

## 4 RESULTS AND DISCUSSION

### 4.1 Effect of partial pressure tools on polymer concentrations and pressure drop at different flow rates

In order to verify the validity of the numerical simulation results, the polymer solution with a concentration of 1000 mg/L is selected to carry out experiments and numerical simulation under different flow rates (5, 8, 10, 13, 16, and 20 m$^3$/d). The comparison results are shown in Figure 5.

As can be seen from Figure 5, the experimental results and the numerical simulation results are better and the fitting degree is higher, so the selected numerical simulation method can be used for research.
the concave circle is 1 mm) under different flow rates (5, 8, 10, 13, 16, and 20 m$^3$/d) were numerically simulated and analyzed, and laboratory experiments were conducted. The results are shown in Figures 6 and 7.

As shown in Figure 6, as the flow rate increases, the pressure drop generated by the polymer solution flowing through the partial pressure tool increases. This is because with the increase of flow rate, the velocity of the polymer solution in the partial pressure tool increases, and the change of the velocity at the minimum cross section becomes more severe. According to Bernoulli’s law, the throttling effect of the polymer solution at this position increases, and the pressure drop generated increases. The numerical simulation results have a higher fitting degree with the experimental results under the condition of low flow rate, but with the increase of the flow rate, the experimental results are larger than the numerical simulation results, and the larger the flow rate, the larger the error. This is because the distance between the throttling groove and the outer cylinder is small, and the polymer solution will stay at the minimum cross section to a certain extent during the flow process, resulting in blocking of the polymer solution in the flow channel, reduction of effective flow area, increase of flow resistance to the solution, resulting in reduction of flow pressure, and increase of pressure drop. As the concentration of the polymer solution increases, the pressure drop of the solution increases, so the pressure drop effect of the partial pressure tool on a high-concentration polymer solution is more obvious.

As shown in Figure 7, as the flow rate increases, the viscosity loss rate of the polymer solution flowing through the partial pressure tool increases. This is because with the increase of flow rate, the shearing degree of the polymer solution in the partial pressure tool increases, the shearing stress generated at the minimum cross section increases, and the stretching degree of the molecular chain increases, resulting in an increase in the viscosity loss rate. However, the numerical simulation results are smaller than the experimental results, and with the increase of the flow rate, the difference of viscosity loss rate is larger. This is because with the increase of the flow rate, the degree of stretching of the polymer molecules increases, causing the molecular chain of the polymer solution to fracture, which cannot be restored to its original state due to elasticity at the maximum cross section. However, the numerical simulation method is only based on the gradual accumulation of finite element analysis and calculation of power-law fluid, and cannot simulate the shearing and stretching effect between molecules. Moreover, the structure of the molecular chain changes at all times during the flow of the polymer solution in the partial pressure tool, resulting in the experimental results being larger than the numerical simulation results. Moreover, the higher the concentration of the polymer solution, the greater the viscosity loss rate of the solution under the action of the partial pressure tool, and the greater the viscosity loss rate of high-concentration polymer solution with the increase of the flow rate.

4.2 Study on flow characteristics of the polymer solution in the partial pressure tool

4.2.1 Velocity

Figures 8-10 show the velocity nephogram, velocity streamline, and velocity change of polymer solution in the partial pressure tool when the flow rate is 10 m$^3$/d, respectively. It can be seen from Figures 8 and 10 that the color change of the velocity nephogram is the most obvious when the flow cross section of the polymer solution is the smallest (the distance between the outer cylinder and the throttling groove is the smallest), which indicates that the degree of velocity change is the largest and the velocity reaches the maximum value of 2.06 m/s at the smallest cross section. When the solution is at the place with the largest
flow cross section (the place with the largest distance between the outer cylinder and the throttling groove), with the expansion of the flow space, the nephogram color does not change obviously, indicating that the speed change degree is small and the speed decreases to the minimum value. It can be seen from Figure 9 that when the flow cross section is the smallest, the
streamline is most closely concentrated. When the solution is at the largest flow cross section, the change of streamline direction is more complicated and changeable, and a vortex is formed at the largest flow channel cross section. This is because of the influence of the shape of the flow channel, which produces jet flow at the minimum flow channel. When the fluid enters the expanded area of the flow channel, the flow channel loses its function of restricting flow due to the inertia of the fluid, and a certain degree of free flow develops, resulting in the change of flow direction. As the polymer solution flows in a variable cross section, it is a process of contraction before expansion and changes periodically, so the velocity and streamline of the polymer solution in the partial pressure tool change periodically.

4.2.2 | Pressure

Figures 11 and 12 show the pressure nephogram and pressure change curve of the polymer solution in the partial pressure tool when the flow rate is 10 m³/d. It can be seen from the figures that when the solution flows through the partial pressure tool, the pressure gradually decreases. According to Bernoulli’s law and the velocity distribution of the polymer solution in the partial pressure tool, the velocity reaches the maximum at the minimum cross section, resulting in the pressure drop and the maximum pressure drop degree. Microscopically, during the flowing process of the polymer solution, the polymer molecular chain is always in a deformation process of elongation and contraction, so that part of energy is consumed on the deformation and recovery of the polymer molecular chain, thus generating local energy loss and forming a throttling pressure difference. However, the polymer solution flows periodically in the throttling groove of the partial pressure tool, so the pressure also shows a periodic downward trend, and the position and range of the pressure change of the polymer solution in the adjacent pressure reducing groove are basically the same. In Figure 9, the streamline direction at the bottom of the maximum cross section of the flow channel is different from the direction along the wall surface, resulting in a vortex, which increases
the energy dissipation of the solution in the flow process and further reduces the pressure.\textsuperscript{28,59,60} According to the pressure curve, the pressure decreases step by step along the flow direction. The pressure decreases faster at the minimum annular space. The pressure drop capability of the polymer solution in each throttling groove is limited. However, the pressure drop of the solution in the flow process of the partial pressure tool is a gradual accumulation process, resulting in the pressure drop of the polymer solution in the pressure dividing tool reaching $6.08 \times 10^5$ Pa.

### 4.2.3 Viscosity

Figures 13 and 14 show the viscosity nephogram and viscosity change curve of the polymer solution in the partial pressure tool when the flow rate is 10 m$^3$/d. From the nephogram, it can be seen that the distribution of viscosity in the flow space is not uniform. When the polymer solution flows through the place with the smallest cross-sectional area, the viscosity of the solution decreases, and the minimum viscosity is near the wall surface at the place with the smallest cross section. After passing through the place with the smallest cross section, the viscosity increases with the increase of the flow space when the polymer solution flows through the place with the largest cross-sectional area. This is because the polymer solution molecules are subjected to high speed shearing and tensile stress in the flowing process, and the shearing action is strongest when the cross section is the smallest, so that short chains and long molecular chains with polar groups in the solution are sheared to stretch and become long or even broken. Additionally, the stretching property of the molecular chains is poor, so that the original network structure becomes incomplete and the meshes become sparse, and the ability of the network structure to wrap water molecules is reduced, resulting in the reduction of viscosity and macroscopically showing the reduction of the viscosity of the
solution. However, with the increase of the flow space, the flow state of the solution is diffusion-like. Due to the elasticity of the molecular chain, it can generate an elastic restoring force after stretching, causing the molecular chain to shrink and the overall structure to become compact, with a macroscopic increase in viscosity. From the viscosity curve, it can be seen that in the periodic shearing process, the shearing effect is greater than the elastic recovery effect, which leads to a viscosity reduction of the polymer solution. After the accumulation of the shearing effect of the throttling unit, the viscosity of the polymer solution decreases by 6.69%.

4.2.4 Strain rate

Figures 15 and 16 show the strain rate nephogram and the strain rate change curve of the polymer solution in the partial pressure tool when the flow rate is 10 m³/d. As can be seen from the figures, when the polymer solution flows through the partial pressure tool, the strain rate of the solution reaches the maximum value 10 236 s⁻¹ at the minimum cross section, the position of the maximum strain rate is close to the wall surface and distributed in an elongated shape along the flow direction, and the strain rate at the center of the minimum cross section is higher than the strain rate close to the outer wall of the throttling groove and the groove bottom. With the increase of flow space, the strain rate gradually decreases, and the strain rate is the smallest when the cross section is the largest, thus the cyclic reciprocation presents periodic changes. On the one hand, the increase in strain rate is due to the increase in the velocity gradient between the main flow region and the wall region, thus increasing the shearing effect on the solution. On the other hand, due to the increase of turbulence.
velocity pulsation in the main flow region, the polymer molecular chain fracture is intensified.\textsuperscript{20,70,71} However, the average strain rate can reflect the degree of shearing when the solution flows through the partial pressure tool, so it can be used to reflect the degree of viscosity reduction.\textsuperscript{72,73} When the strain rate reaches the maximum, the energy loss of the polymer solution is greater, and the pressure drop and the greater the viscosity loss at that location are greater. The effect of strain rate on the pressure and viscosity of the polymer solution conforms to the change of pressure and the viscosity nephogram.

4.3 Optimization of the structural parameters of the partial pressure tool

Pressure drop and viscosity loss rate are important parameters that reflect the performance of the partial pressure tool. There are many influencing factors. For the partial pressure tool, the main structural parameters are the distance between the throttling groove and the outer cylinder, the radius of the convex circle, and the radius of the concave circle.

In the process of oil displacement, when a partial pressure tool is used to generate a large pressure drop, the viscosity
loss of the displacement agent must be minimized to avoid affecting the oil displacement effect of the displacement agent in a high-permeability oil layer.

In order to match the production requirements of the oilfield, Daqing oilfield has given the structural parameters of the partial pressure tool according to the downhole injection conditions of the actual formation, as shown in Table 4. In this paper, by means of numerical simulation and orthogonal test, the optimal combination of structural parameters is proposed to meet the requirements of the partial pressure tool for the polymer solution to produce a larger pressure drop and a smaller viscosity loss rate.

Since the influence of each parameter on performance is not clear, there are 27 schemes for all the permutations and combinations. In order to improve the effectiveness of the optimization design of the numerical simulation structure, this optimization design introduces the principle of orthogonal experiment design into the optimization of the numerical simulation of the throttle groove structure parameters. Orthogonal experiment design can obtain more information with less repetition of experiments, which can significantly reduce the complexity and workload of the design and achieve the purpose of prediction, control, and optimization. Through the comprehensive evaluation of the evaluation indexes, the optimal throttle structure parameters with the maximum pressure drop and the minimum viscosity loss rate can be obtained. This simulation is a 3-factor 3-level numerical simulation experiment. Without considering the influence of interference between various structural parameters, nine groups of experiments were designed by using an $L_9(3^3)$ orthogonal table, as shown in Table 5.

In this orthogonal experiment, there were two indexes, namely pressure drop (Pa) and viscosity loss rate (%). The greater the pressure drop the better, and the smaller the viscosity loss the better. The pressure drop and viscosity loss rate calculated by the numerical simulation when the flow rate was 10 m$^3$/d are shown in Table 6.

According to the orthogonal experiment, through the analysis of the two indexes of pressure drop (Pa) and viscosity loss rate (%), it can be seen that different indexes have different

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**FIGURE 16** Strain rate change curve

**TABLE 4** Level table of experiment factors for partial pressure tools

| Design scheme | A | B | C |
|---------------|---|---|---|
|               | Distance between the throttling groove and the outer cylinder (mm) | Radius of convex circle (mm) | Radius of concave circle (mm) |
| 1             | 0.5 | 3  | 1  |
| 2             | 1   | 3.5| 1.5 |
| 3             | 1.5 | 4  | 2  |
optimal selection results. According to the pressure drop and viscosity loss rate results in Table 4, the primary and secondary order and influence degree of each index can be analyzed by using the analysis method of the orthogonal experiment results, and the analysis results are shown in Table 5.

In Table 7, $k$ is the average of factors, which is an index to judge the degree of influence of different structural parameters in each factor. If the calculated factor value is larger, and the corresponding maximum value of $k$ value should be selected. If the calculated factor value is smaller, the corresponding minimum value of $k$ should be selected. The range $r$ is the difference between the maximum value and the minimum value in the average value $k$, and the greater the range, the greater the effect of this factor. Therefore, according to the pressure drop index, the primary and secondary order of influence degree of each structural factor is ACB (distance between the throttling groove and the outer cylinder > convex circle radius > concave circle radius). According to the principle of maximum pressure drop, the preferred scheme is $A_1B_3C_1$ (distance between the throttling groove and the outer cylinder is 0.5 mm, convex circle radius is 4 mm, concave circle radius is 1 mm). According to the index of viscosity loss rate, the primary and secondary order of influence degree of each structural factor is CBA (concave circle radius > convex circle radius > distance between the throttling groove and the outer cylinder). According to the principle of minimum viscosity loss rate, the preferred scheme is $A_3B_1C_1$ (distance between the throttling groove and the outer cylinder is 1.5 mm, convex circle radius is 3 mm, and concave circle radius is 1 mm). In the end, the selected optimal scheme should take into account each index, so the required factor level is different. Therefore, based on the results of orthogonal analysis, the comprehensive balance analysis method was used to select the optimal parameter combination. Variance analysis results of pressure drop and viscosity loss rate of various factors and different structural parameters of the partial pressure injection tool are shown in Tables 8 and 9.

From the analysis in Tables 6 and 7, it can be seen that the contribution rates of the distance between the throttling groove and the outer cylinder, convex circle radius, and concave circle radius to the pressure drop are 99.9728%, 0.0058%, and 0.0214%, respectively. Among the three structural factors, the distance between the throttling groove and the outer cylinder of the partial pressure injection tool has the most significant effect on the pressure drop, accounting for 99.9728%, while the convex circle radius and concave circle radius have less effect on the pressure drop (<2%).

However, the contribution rates of the distance between the throttling groove and outer cylinder, convex circle radius and concave circle radius to the viscosity loss rate are 15.6446%, 3.6089%, and 80.7455%, respectively. It can be seen from this that among the three structural factors of the throttling groove of the partial pressure injection tool, the concave circle radius

### Table 5 Orthogonal table of structural schemes

| Design scheme | Experiment factor | Distance between the throttling groove and the outer cylinder (mm) | Radius of convex circle (mm) | Radius of concave circle (mm) |
|---------------|-------------------|---------------------------------------------------------------|-----------------------------|-----------------------------|
| 1             | A                 | 0.5                                                          | 3                           | 1                           |
| 2             | A                 | 0.5                                                          | 3.5                         | 1.5                         |
| 3             | A                 | 0.5                                                          | 4                           | 2                           |
| 4             | A                 | 1.5                                                          | 3                           | 1.5                         |
| 5             | A                 | 1.5                                                          | 3.5                         | 2                           |
| 6             | A                 | 1.5                                                          | 4                           | 1                           |
| 7             | A                 | 1.5                                                          | 3                           | 2                           |
| 8             | A                 | 1.5                                                          | 3.5                         | 1                           |
| 9             | A                 | 1.5                                                          | 4                           | 1.5                         |

### Table 6 Simulation results of partial pressure tools with different structural parameters

| Design scheme | Experiment factor | Pressure drop (Pa) | Viscosity loss rate (%) |
|---------------|-------------------|--------------------|-------------------------|
| 1             | A                 | 608558             | 6.69                    |
| 2             | A                 | 635524             | 7.05                    |
| 3             | A                 | 584652             | 8.24                    |
| 4             | A                 | 377849             | 7.83                    |
| 5             | A                 | 363861             | 8.34                    |
| 6             | A                 | 434178             | 7.92                    |
| 7             | A                 | 230847             | 5.58                    |
| 8             | A                 | 265675             | 7.17                    |
| 9             | A                 | 267120             | 5.94                    |
has the most significant influence on the viscosity loss rate, accounting for 80.7455%, while the distance between the throttling groove and the outer cylinder and the convex circle radius have the same obvious influence on the viscosity loss rate, accounting for 15.6446% and 3.6089%, respectively.

According to the results of variance analysis, for factor $A$ (distance between throttling groove and outer cylinder), its contribution rate to the pressure drop and viscous loss rate is relatively large, reaching 99.9728% and 15.6446%, respectively, and both of these indexes increase with the increase of a level value, so the selection of the two indexes is contradictory. However, since the main function of the partial pressure tool is to achieve a certain pressure drop, we selected the structural parameter that caused the largest pressure drop, namely the distance between the throttling groove and the outer cylinder to be 0.5 mm. In terms of factors $B$ (convex circle radius) and $C$ (concave circle radius), their effects on the pressure drop are relatively small at only 0.0058% and 0.0214%, both <2%, while their effects on viscosity loss are relatively large at 3.6089% and 80.7455%, so for factors $B$ and $C$ the structural parameters most favorable for reducing viscosity loss, convex circle radius 3 mm and concave circle radius 1 mm, were selected.

Through the variance analysis method and comprehensive analysis method calculation, considering the factors of pressure drop and viscosity loss comprehensively, in order to meet the requirements of a larger pressure drop and smaller viscosity loss rate, the optimal structural parameters of the throttling groove of the partial pressure tool are $A_1B_1C_1$; namely, the distance between the throttling groove and the outer cylinder is 0.5 mm, the convex circle radius is 3 mm, and the concave circle radius is 1 mm.
4.4 Field test study

Daqing Oilfield has developed a partial pressure tool (as shown in Figure 17) according to the research on the flow characteristics of the displacement agent in the partial pressure tool through numerical simulation and laboratory experiments, and carried out field tests in the North Second West East Block of No. 1 Oil Production Plant. Under the condition of 2.5 times of permeability ratio, the oil recovery changes of the oilfield blocks before and after the partial pressure tool was used in the later stage of polymer injection in this block were counted, as shown in Table 8.

From the production data in Table 10, it can be seen that stratified polymer injection can further improve the oil recovery by 2.54% compared with traditional polymer injection. Therefore, for reservoirs with serious heterogeneity, partial pressure tools can be used in the oil displacement process to effectively improve the oil recovery.

5 Conclusion

In this paper, the flow characteristics of polymer solution in a partial pressure tool were studied by numerical simulation and laboratory experiments, and the structural parameters of the partial pressure tool were optimized by orthogonal experiments. The following conclusions were obtained:

1. During the flow of polymer solution in the partial pressure tool, the velocity and strain rate reach the maximum at the minimum cross section of the flow space,
resulting in a larger pressure drop and viscosity loss at the minimum cross section of the polymer solution. The polymer solution passes through each throttling unit and receives the same effect. The pressure drop, velocity, viscosity, and strain rate all change periodically.

2. Numerical simulation and laboratory experiments show that the partial pressure tool has an obvious depressurization effect on the polymer solution. The greater the increase of the flow rate, the greater the pressure drop and viscosity loss rate of the partial pressure tool to the polymer solution, and the higher the concentration of the polymer solution, the greater the pressure drop and viscosity loss rate of the partial pressure tool to the solution.

3. According to orthogonal experiments, the optimal structural parameters of the partial pressure tool that can produce a larger pressure drop and smaller viscosity loss rate are a distance between the throttling groove and outer cylinder of 0.5 mm, a radius of the convex circle of 3 mm, and a radius of the concave circle of 1 mm.

4. For reservoirs with severe heterogeneity, partial pressure tools can effectively improve oil recovery.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

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REFERENCES
1. Denny D. Effect of elasticity on displacement efficiency: high concentration polymer flooding. J Pet Technol. 2009;61:50-51.
2. Wassmuth FR, Gree NK. Polymer flood application to improve heavy oil recovery at east bodo. J Can Pet Technol. 2009;48:55-61.
3. Clark SR. Design and application of an alkaline-surfactant-polymer recovery system for the West Kiehl field. SPE Adv Technol Ser. 1993:1:172-179.
4. Wang Y, Sun S, Gong L, Yu B. A globally mass-conservative method for dual-continuum gas reservoir simulation. J Nat Gas Sci Eng. 2018;53:301-316.
5. Cao WJ, Xie K, Lu XG, Liu YG, Zhang YB. Effect of profile-control oil-displacement agent on increasing oil recovery and its mechanism. Fuel. 2019;237:1151-1160.
6. Li HC. Overview of separate injection technique for polymer flooding in Daqing oilfield. Oil Gas Geol. 2012;33:296-301.
7. Geng CH, Liu QW. Study on polymer single pipe layered injection process. Pet Geol Oilfield Dev Daqing. 2006;25:38-41.
8. Zhou ZJ, Zhao JB, Zhou T, Huang YM. Study on in-depth profile control system of low-permeability reservoir in block H of Daqing oilfield. J Petrol Sci Eng. 2017;157:1192-1196.
9. Zhao G, Dai CL, Chen A, Yan ZH, Zhao MW. Experimental study and application of gels formed by nonionic polyacrylamide and phenolic resin for in-depth profile control. J Petrol Sci Eng. 2015;135:552-560.
10. Liu YF, Dai CL, Wang K, et al. Investigation on preparation and profile control mechanisms of the dispersed particle gels (DPG) formed from phenol-formaldehyde cross-linked polymer gel. Ind Eng Chem Res. 2016;55:6284-6292.
11. Zhao G, You Q, Tao JP, et al. Preparation and application of a novel phenolic resin dispersed particle gel for in-depth profile control in low permeability reservoirs. J Pet Sci Technol. 2018;161:703-714.
12. Yao C, Lei GL, Li L, Gao XM. Selectivity of pore-scale elastic microspheres as a novel profile control and oil displacement agent. Energy Fuels. 2012;26:5092-5101.
13. Li YS, Li ZM, Li BF. Experimental study and application on profile control using high-temperature foam. J Petrol Sci Eng. 2011;78:567-574.
14. Liu PC, Zhang XK, Wu YB, Li XL. Enhanced oil recovery by air-foam flooding system in tight oil reservoirs: study on the profile-controlling mechanisms. J Petrol Sci Eng. 2017;150:208-216.
15. Li SY, Qiao CY, Ji GW, Wang Q, Tao L. Experimental study of profile control with foam stabilized by clay particle and surfactant. Energies. 2019;12:781.
16. Tian MJ, Guo YH, Li YQ, Guo HH. Research on a new faucet with the function of depressurization and throttling. Adv Mater Res. 2014;945:253-256.
17. Aadnoy BS, Ravnoy JM. Improved pressure drop/flow rate equation for non-Newtonian fluids in laminar flow. J Petrol Sci Eng. 1994;11:261-266.
18. Hu G, Zhang P, Wang GR, et al. Performance study of erosion resistance on throttle valve of managed pressure drilling. J Petrol Sci Eng. 2017;156:29-40.
19. Sun X, Ni HJ, Wang RH, Shen ZH, Zhao MY. Characteristic study on supercritical carbon dioxide impinging jet: calculation and stagnation properties analysis. J Petrol Sci Eng. 2018;162:532-538.
20. Wu DY, Zhang SH, He Y. A dynamic mesh-based approach to analyse hydrodynamic interactions between a fluidic hammer and drill bit. J Petrol Sci Eng. 2019;175:536-546.
21. Wang C, Liu GH, Li J, et al. New methods of eliminating downhole WOB measurement error owing to temperature variation and well pressure differential. J Petrol Sci Eng. 2018;171:1420-1432.
22. Li JB, Li GS, Huang ZW, Song XZ, He ZG, Zhang SK. A discussion about the method to study the effect of ambient pressure on hydraulic jetting. J Petrol Sci Eng. 2017;149:203-207.
23. Tasmi T, Rahmawati SD, Sukarno P, Soewono E. Applications of line-pack model of gas flow in intermittent gas lift injection line. J Petrol Sci Eng. 2017;157:930-940.
24. Banerjee S, Hascakir B. Flow control devices in SAGD completion design: enhanced heavy oil/ bitumen recovery through improved thermal efficiency. J Petrol Sci Eng. 2018;169:297-308.
25. Fang C, Ma SH, Cai BH, Yu J. Optimization design and simulation study of multi stage throttling noise reduction for high pressure differential water injection system. Fluid Mach. 2017;45:33-37.
26. Yan TJ, Zhao XH, Wang XH, Yu JF, Shi YF. Study on energy conservation water injection system of offshore platform based on jet pump. J Petrol Sci Eng. 2018;170:368-373.
27. Liu YQ, Wang CY, Cai JB, Lu H, Huang LY, Yang Q. Pilot application of a novel Gas-Liquid separator on offshore platforms. J Petrol Sci Eng. 2019;180:240-245.
28. Perissinotto RM, Verde WM, Gallassi M, et al. Experimental and numerical study of oil drop motion within an ESP impeller. J Petrol Sci Eng. 2019;175:881-895.
29. Ma Y, Ni Y, Zhang H, Zhou SQ, Deng HY. Influence of valve's lag characteristic on pressure pulsation and performance of reciprocating multiphase pump. J Petrol Sci Eng. 2018;164:584-594.

30. Pietrzak M, Witczak S. Experimental study of air–oil–water flow in a balancing valve. J Petrol Sci Eng. 2015;133:12-17.

31. Zhang HR, Liang YT, Zhou XY, Yan XH, Qian C, Liao Q. Sensitivity analysis and optimal operation control for large-scale waterflooding pipeline network of oilfield. J Petrol Sci Eng. 2017;154:38-48.

32. Augustine JR, McIntyre A, Adam RJ. Increasing oil recovery by preventing early water and gas breakthrough in a west bre horizontal well: a case history. In: Proceedings of the SPE/DOE Symposium on Improved Oil Recovery, Tulsa, Oklahoma, USA, 2006.

33. Henriksen KH, Gule EI, Case AJR. Case study: the application of inflow control devices in the troll field. In: Proceedings of the SPE Europe/EAGE Annual Conference and Exhibition, Vienna, Austria, 2006.

34. Coronado MP, Garcia L, Russell R, Garcia GA, Peterson ER. New inflow control device reduces fluid viscosity sensitivity and maintains erosion resistance. In: Proceedings of the Offshore Technology Conference, Houston, Texas, 2009.

35. Least B, Greci S, Wileman A, Uford A. Fluidic diode autonomous inflow control device range 3B - oil, water, and gas flow performance testing. In: Proceedings of the SPE Kuwait Oil and Gas Show and Conference, Kuwait City, Kuwait, 2013.

36. Garcia GA, Coronado MP, Gavioli P. Identifying well completion problems and inflow control device performance. In: Proceedings of the SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, 2009.

37. Stoffa H. Incompressible flow in a labyrinth seal. J Fluid Mech. 1980;100:817-829.

38. Huang B, Hu XY, Fu C, Liu CJ, Wang Y, An X. Rheological model and transition velocity equation of a polymer solution in a partial pressure tool. Polymers. 2019;11:855.

39. Vermes G. A fluid mechanics approach to the labyrinth seal leak-off problem. J Eng Power. 1961;83:161-169.

40. Rhode DL, Sobolik SR. Simulation of subsonic flow through a generic labyrinth seal. J Eng Gas Turbines Power. 1986;108:674-680.

41. Paschek D, Krishna R. Kinetic Monte Carlo simulations of transport diffusivities of binary mixtures in zeolites. Phys Chem Chem Phys. 2001;3:3185-3191.

42. Martin MG, Thompson AP. Effect of pressure, membrane thickness, and placement of control volumes on the flux of methane through thin silicate membranes: a dual control volume grand canonical molecular dynamics study. J Chem Phys. 2001;114:7174-7181.

43. Ahunbay MG, Elliott JR. Surface resistance to permeation through the silicate single crystal membrane: variation with permeant. J Phys Chem B. 2004;108:7801-7808.

44. Wang Y, Wang Y, Cheng Z. Direct numerical simulation of gas-liquid drag-reducing cavity flow by the VOSET method. Polymers. 2019;11:1-17.

45. Wang Y, Yu B, Wang Y. Acceleration of gas reservoir simulation using proper orthogonal decomposition. Geofluids. 2018;8482352:1-15.

46. Launder BE, Spalding DB. Lectures in Mathematical Models of Turbulence. London, UK: Academic Press; 1972.

47. Seyedsbagheri H, Mirzayi B. CFD modeling of high inertia asphaltene aggregates deposition in 3D turbulent oil production wells. J Petrol Sci Eng. 2016;150:257-264.

48. Wang Y, Sun S, Yu B. Acceleration of gas flow simulations in dual-continuum porous media based on the mass-conservation POD method. Energies. 2017;10:1-17.

49. Stress R. Model for viscoelastic drag-reducing flow induced by polymer solution. Polymers. 2019;11:1-12.

50. Shi Y, Zhu HW, Zhang JY, Zhang JT, Zhao JL. Experiment and numerical study of a new generation three-stage multiphase pump. J Petrol Sci Eng. 2018;169:471-484.

51. Azadi M, Aminossadati SM, Chen ZW. Development of an integrated reservoir-wellbore model to examine the hydrodynamic behaviour of perforated pipes. J Petrol Sci Eng. 2017;156:269-281.

52. Wong SF, Dol SS, Wee SK, Chua HB. Micro-litre crude water-in-oil emulsions characterization – rheological behaviour, stability and amount of emulsions formed. J Petrol Sci Eng. 2018;165:58-66.

53. Huang B, Li XH, Fu C, Wang Y, Cheng HR. Study rheological behavior of polymer solution in different-medium-injection-tools. Polymers. 2019;11:319.

54. Xin XK, Yu GM, Chen ZX, Wu KL, Dong XH, Zhu ZY. Effect of polymer degradation on polymer flooding in heterogeneous reservoirs. Polymers. 2018;10:857.

55. Bird BR, Armstrong RC, Hassager O. Dynamics of Polymeric Liquids, Vol. 1 (DPL1). Hoboken, NJ: John Wiley and Sons Ltd; 1987.

56. Tao R, Wang ZW. Analysis of the guide vane jet-vortex flow and the induced noise in a prototype pump-turbine. Appl Sci. 2019;9:1971.

57. Wang Y, Sun S. Direct calculation of permeability by high-accurate finite difference and numerical integration methods. Commun Comput Phys. 2016;20:405-440.

58. He MJ, Chen WX, Dong X. Polymer Physics. Shanghai, China: Fudan University Press; 2000.

59. Yu GB, Chen JH, Li JR, Hu T, Wang S, Lu HL. Analysis of SO2 and NOx emissions using two-fluid method coupled with Eddy dissipation concept reaction submodel in circulating fluidized bed combustors. Energy Fuels. 2014;28:2227-2235.

60. Gallego F, Shah SN. Friction pressure correlations for turbulent flow of drag reducing polymer solutions in straight and coiled tubing. J Petrol Sci Eng. 2009;65:147-161.

61. Wang JR, Han DW, Lu XG, Guo Q, Yang HJ, Zhang J. Effect of polymer concentration on solution seepage characteristics and reasonable concentration limit. Oilfield Chem. 2015;32:237-241.

62. Zhu HJ, Luo JH, Sui XG, et al. Microstructure of novel polymer solution used for oil displacement. Acta Petrol Sin. 2006;27:79-83.

63. Shchetnikava V, Slot J, Ruymbeke VE. Comparative analysis of different tube models for linear rheology of monodisperse linear entangled polymers. Polymers. 2019;11(5):754.

64. Qian Y, An XW, Huang XF, Pan XQ, Zhu J, Zhu XL. Recyclable self-healing polyurethane cross-linked by alkyl diselenide with enhanced mechanical properties. Polymers. 2019;11(5):773.

65. Wu Q, Li XW, Li Q, Wang SQ, Luo Y. Estimation of aspect ratio of cellulose nanocrystals by viscosity measurement: influence of aspect ratio distribution and ionic strength. Polymers. 2019;11(5):781.

66. Yan ZC, Biswas CS, Stadler FJ. Rheological study on the thermoreversible gelation of stereo-controlled poly(N-isopropylacrylamide) in an imidazolium ionic liquid. Polymers. 2019;11:783.

67. Xia L, Gao H, Bi W, Fu WX, Qiu GX, Shape XZX. Memory characteristic on pressure pulsation and performance of reciprocating multiphase pump. Oilfield Chem. 2015;32:237-241.
vulcanization: mechanical, rheological, crystalline, thermal, and UV protective property. *Polymers*. 2019;11:1108.

69. Alwazzan A, Than CK. Linear stability analysis and experimental verification of stratified air–water flow in a horizontal bend. *J Petrol Sci Eng*. 2006;50:299-307.

70. Santim CGS, Gaspari EF, Paternost GM. A transient analysis of gas-liquid slug flow inside a horizontal pipe using different models. *J Petrol Sci Eng*. 2017;151:62-76.

71. Oliveira GMD, Franco AT, Negrao COR, Martins AL, Rodrigo AS. Modeling and validation of pressure propagation in drilling fluids pumped into a closed well. *J Petrol Sci Eng*. 2013;103:61-71.

72. Migler K, Liu CH, Pine DJ. Structure evolution of a polymer solution at high shear rates. *Macromolecules*. 1996;29:1422-1432.

73. Ram A, Siegman A. Intrinsic viscosity of polymer solutions at high shear rates. *J Appl Polym Sci*. 1968;12:59-69.

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