Effect of a Partial Pressure Tool on Improving the Heterogeneous Oil Recovery and Polymer Solution Microstructure

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ABSTRACT: To improve the oil displacement effect of polymer solutions in heterogeneous oil layers and increase the energy utilization rate, Daqing Oilfield proposes a partial pressure tool to control the polymer solution injection amount in high-permeability oil layers and increase the injection amount in low-permeability oil layers to enhance the total oil recovery. To study the effect of the partial pressure tool on enhancing oil recovery and the action mechanism of the tool on polymer molecules in high-permeability reservoirs, core displacement experiments were performed to study the effects of various factors on oil recovery. Microscopic experiments were then carried out to study the differences in molecular morphology and molecular coil size of the microscopic polymer solution before and after the action of the partial pressure tool. The experimental results show that the partial pressure tool increased the oil recovery by 4.4% and that the throttling pressure difference was directly proportional to the oil recovery. The partial pressure tool subjected the polymer solution to shear deformation and reduced the molecular coil size. When the concentration of the solution was changed, the degree of change in the molecular structure and the coil size was small, and the influence on the oil displacement effect was minimal. This experiment is of great significance for improving the energy utilization rate.

1. INTRODUCTION

Oil fields that have been exploited for a long time enter the high water cut stage.1−3 This stage is characterized by high water cut and low energy utilization caused by reservoir heterogeneity and an unfavorable mobility ratio. However, there is still a large amount of residual oil left in the formation after conventional oil displacement.4−6 To ensure stable production and to improve the energy utilization rate, polymer flooding is increasingly employed to enhance oil recovery in various oil fields.7−9 The oil reservoirs are usually heterogeneous. When polymer flooding is carried out in high-permeability oil layers, the polymer solution has strong injection capacity, large injection volume, and good flooding effect. In contrast, in low-permeability layers, the injected solution has poor matching to the reservoir and hence low injection volume and poor flooding effect.10−16 In order to improve the oil displacement effect, a partial pressure tool is proposed for use in high-permeability oil layers. The tool increases the polymer injection amount in low-permeability oil layers and enhances the total oil recovery without affecting the oil displacement effect of the polymer solution in the high-permeability oil layers.

To date, improvements have been made to traditional polymer flooding to enhance oil recovery. Technical processes for surfactant/polymer flooding and alkali/surfactant/polymer flooding have been put forward, and the synergistic effect of various chemicals has been used to improve the flooding effect.17−20 Some researchers have also developed new polymers to improve the oil displacement effect.21,22 However, these technologies cannot solve the issue of reservoir heterogeneity.23 Although they can greatly enhance the oil recovery from high-permeability reservoirs, they cannot enhance the oil recovery from low-permeability reservoirs. The total oil recovery is still low. Therefore, some researchers have investigated the improvement of oil recovery in heterogeneous reservoirs. Currently, profile control in high-permeability reservoirs is the most effective method to enhance the low oil recovery caused by reservoir heterogeneity. Liu et al.24 studied the new prole control agent of dispersed particle gel (DPG) and conducted a parallel sand layer filling test and a microscopic visualization test. The experimental results show that DPG particles can block the high-permeability layer by gathering in the large pore throats or directly blocking small pore throats and hence improve the sweep efficiency and oil recovery and realize deep profile control.24 Yao et al.25 studied pore-scale elastic microspheres as a new profile control agent and carried out displacement experiments. The results show that the elastic microspheres are
more likely to block the high-permeability layer. The elastic microspheres block water and oil and can improve the sweep condition and oil displacement effect in the high-permeability, medium-low-permeability, and low-permeability layers. Liu et al. studied asphalt particle gel (GAP) as a new composite profile control system and conducted core displacement experiments. Laboratory core displacement experiment results show a good injectivity of the GAP solution in the high-permeability zone with a high plugging rate. Parallel core displacement experiment results demonstrate a longer response time and enhanced oil recovery for GAP compared to polymer gels in fractured systems. Lu et al. studied the factors affecting the production increase by depth profile control agents and their reservoir adaptability by core displacement experiments. The results show that the dosage, strength, and permeability coefficient of the oil displacement agent all affect the profile control stimulation effect, which improves with larger injection volumes. The oil recovery initially increases with agent concentration and then decreases as the agent concentration is increased further. Shi et al. studied self-aggregated divinylbenzene-co-acrylamide (DCA) microspheres as a new profile control agent and the influence of different ratio factors on oil recovery through core displacement experiments. The results show that the oil recovery enhancement is the highest when DCA microspheres with the optimal matching factor are injected. Additionally, the oil saturation distribution demonstrates that these DCA microspheres can enhance the sweep efficiency by plugging high-permeability water channels.

Although profile control can obviously enhance the oil recovery from heterogeneous reservoirs, the injected profile control agent will block the high-permeability reservoirs after profile control is performed. In addition, some profile control agents will enter the low-permeability reservoirs and remain in the matrix, thus polluting the low-permeability reservoirs. Therefore, an oil displacement method that neither pollutes the formation nor changes its structure to improve the heterogeneity of the oil layer is highly significant. To address these requirements, Daqing Oilfield has put forward a concept of oil displacement by layered injection. In layered injection, a partial pressure tool is used to control the injection amount in high-permeability oil layers to increase the displacement agent injection amount in low-permeability oil layers and improve the total oil recovery. Corresponding research has been carried out in order to study the effectiveness of the partial pressure tool in enhancing oil recovery. Huang et al. established the physical model of the partial pressure tool and the rheological equation of the polymer solution in the tool using force balance analysis and then analyzed the influence of the partial pressure tool structural parameters on the rheological properties of the polymer solution. Huang et al. studied the flow characteristics of the polymer solution in the partial pressure tool by finite element analysis and verified the results of the numerical simulation through laboratory experiments. The optimal structural parameters of the partial pressure tool were obtained from the experiments. At a flow rate of 10 m³/day, the partial pressure tool achieved a pressure drop of 6.08 × 10⁴ Pa in the polymer solution and a viscosity loss rate of 6.69%. Although the flow characteristics of the polymer solution in the partial pressure tool have been studied in the works above, the flow characteristics were only studied from the perspective of theoretical formulae and numerical simulations. Experimental proof of the oil recovery enhancement by the partial pressure tool and the effect of the tool on the polymer solution molecules is still lacking.

In this paper, an experimental model of layered injection was established based on the partial pressure tool. Polymer solutions with different molecular weights and concentrations and cores with different permeability ranges were selected for displacement experiments to study the effect of the partial pressure tool on enhancing oil recovery. The relationships between throttling pressure difference, polymer solution concentration, polymer molecular weight, and the oil recovery by the polymer solution flowing through the partial pressure tool were also studied.

## 2. RESULTS AND DISCUSSION

### 2.1. Influence of Partial Pressure Tool on Oil Recovery

Heterogeneous cores with a permeability ratio of 3 were selected for displacement experiments under the condition of low injection volume (10 m³/day) to obtain the polymer solution total oil recovery and throttling pressure. The experiments were performed using polymer solutions with different molecular weights and concentrations with and without the action of the partial pressure tool. The results are shown in Table 1. The oil recovery and throttling pressure difference of each core before and after the polymer solution passed through the partial pressure tool under different permeability ratios were also obtained and shown in Figure 7.

As shown in Table 1, under the condition of low injection volume, the total oil recovery of heterogeneous cores increased after the action of the partial pressure tool. The oil recovery both before and after the action of the partial pressure tool increased with the polymer solution molecular weight. This is because increasing the molecular weight increased the effective volume of the molecules in the solution. The molecular chains were more likely to entangle, forming firmer-networked entanglement points. Macroscopically, the viscosity was also higher, resulting in an increase in the oil displacement efficiency of the solution in the core pore channels. For a given polymer molecular weight, the oil recovery both before and after the action of the partial pressure tool increased with the polymer solution concentration. This is because a higher solution concentration corresponds to an increased density of the polymer molecules. The denser arrangement of polymer molecules tightened the total network structure and led to a higher viscosity and hence a better oil displacement effect in the pores.

Due to the throttling effect of the partial pressure tool, the injection amount of the polymer solution in the high-permeability cores was controlled, and the injection amount in the low-permeability cores was increased, thus improving both the oil displacement efficiency and the total oil recovery. Increasing the polymer solution molecular weight and concentration increased the throttling pressure difference of

| Table 1. Effect of the Partial Pressure Tool |
|---------------------------------------------|
| molecular weight | concentration | total oil recovery before the action of the partial pressure tool (%) | total oil recovery after the action of the partial pressure tool (%) | throttling pressure difference after the action of the partial pressure tool (MPa) |
| 1600 | 2000 | 31.3 | 33.1 | 1.01 |
| 1900 | 1500 | 29.2 | 32.4 | 0.96 |
| 2000 | 1500 | 33.9 | 35.6 | 1.06 |
| 2500 | 2000 | 36.9 | 39.3 | 1.13 |
| 2500 | 2000 | 37.8 | 42.2 | 1.21 |
the polymer solution flowing through the partial pressure tool. This shows that the higher the molecular weight and concentration of the solution, the better are the throttling effect of the partial pressure tool and the control on the injection amount of the polymer solution in high-permeability reservoirs. This is consistent with the increased oil recovery.

The partial pressure tool increased the total oil recovery improvement by 21.3 and 27.5% when the molecular weight and concentration of the polymer solution were changed, respectively. Therefore, changing the concentration of the displacement agent has a more significant effect on enhancing oil recovery when the partial pressure tool is used to improve the oil displacement effect in heterogeneous reservoirs.

Figure 1 shows the results of the displacement experiment when the permeability ratios of the heterogeneous cores were varied at the low injection volume of 10 m$^3$/day, and the polymer solution with a molecular weight of 1900 $\times$ $10^4$ and concentration of 2000 mg/L was used.

It can be seen from Figure 1a that with the increase of the permeability ratio, the oil recovery from the high-permeability core before the action of the partial pressure tool increased, while the oil recovery from the low-permeability core decreased. This is because in the displacement process, before the partial pressure tool was installed, the polymer solution had a strong injection capacity and a large injection amount in the high-permeability core, which led to a better oil displacement effect from the polymer solution. There was a large reduction in the amount of the polymer solution injected in the low-permeability core, which had a poor oil displacement effect. Moreover, with the increase of permeability ratio, more polymer solution was injected into the high-permeability core and less polymer solution was injected into the low-permeability core, resulting in increased polymer solution oil recovery in the high-permeability core and decreased oil recovery in the low-permeability core.

With the same permeability ratio, the polymer solution oil recovery in the high-permeability cores decreased and that in the low-permeability core increased after the action of the partial pressure tool. This is because the injection amount of the polymer solution into the high-permeability core was restricted by the partial pressure tool, which produced a shear effect on the polymer solution.\textsuperscript{32,33} The shear effect changed the properties of the polymer solution, affected the oil displacement effect, and led to a slight decrease in oil recovery. However, the partial pressure tool increased the polymer solution injected into the low-permeability core, enhancing the oil displacement effect and polymer solution oil recovery. As the permeability ratio increased, the throttling effect of the partial pressure tool increased. The throttling pressure difference increased to a maximum of 1.21 MPa, as shown in Figure 1b. Therefore, in the high-permeability core, the stronger the control effect of the partial pressure tool on the polymer solution, the more obvious was the effect on the polymer molecules. This resulted in a slight increase in the degree of oil recovery reduction. An increase in the polymer solution injected into the low-permeability core resulted in a substantial increase in the polymer solution oil recovery.

The increase of oil recovery in the low-permeability core after the action of the partial pressure tool was larger than the decrease of oil recovery in the high-permeability core, which led to an increase in the total oil recovery. The increase is consistent with Figure 1c. The total oil recovery increased with the permeability ratio, with a maximum increase of 4.5%. Therefore,

the oil recovery enhancement of the partial pressure tool increases with the reservoir heterogeneity.

2.2. Influence of the Partial Pressure Tool on the Molecules of the Polymer Solution. Although the partial pressure tool will greatly enhance the polymer solution oil recovery, the throttling effect of the partial pressure tool also affects the polymer solution.
recovery of the polymer solution in low-permeability cores, it will also lead to a slight decrease in the oil recovery in high-permeability cores. This is because when the partial pressure tool is used to control the injection amount of the polymer solution in high-permeability cores, the partial tool will also affect the polymer solution during the injection process by changing the molecular structure of the polymer solution. This affects the oil displacement effect of the polymer solution in high-permeability cores, resulting in the reduction of oil recovery. The influence of the polymer solution concentration and molecular weight on the effect of the partial pressure tool is highly significant, and should be studied from the microscopic aspect. To further understand the effect of the partial pressure tool on the polymer solution molecules in the process of high-permeability core flooding, the microstructure and molecular coils of polymer molecules before and after the action of the partial pressure tool were analyzed.

2.2.1. Influence of the Partial Pressure Tool on the Molecular Microstructure of the Polymer Solution. Cores with a very permeability ratio of 3 and polymer solutions with different concentrations and molecular weights were selected for the displacement experiment at the low injection amount of 10 m³/day. When the experiment has stabilized, the polymer solution before and after the action of the partial pressure tool was sampled and observed by SEM. The results are shown in Figures 2 and 3.

Polymer molecules form a continuous spatial network structure in the solution and have a certain fractal growth self-similarity. This is mainly due to the electrostatic repulsion between adjacent carboxyl groups on the macromolecular chains after the partial hydrolysis of polyacrylamide, which enhances the stretching of the polymer molecular chains. Different polymer molecular chains can penetrate one another and even intertwine, resulting in the formation of high-density multi-layer three-dimensional network structures with holes of different sizes in the solution and the emergence of coarse trunk and subdivision branches. This network structure can adsorb and enwrap large numbers of water molecules to generate deformation resistance, resulting in the good adhesion enhancement capability of the partially hydrolyzed polyacrylamide solution. Further analysis shows that the relative molecular mass of the polymer has an influence on the structure of the molecular aggregation state. Increasing the relative molecular mass lengthens the molecule chains and hence decreases the number of molecular chains contained per unit volume, the intermolecular force, and the density of the molecular space network structure. Increasing the concentration of the solution increases the number of molecules per unit volume of the polymer solution, the entanglement degree and width of the molecular chains, and the tightness of the grid structure.

The scanning electron microscope images of the polymer molecule aggregation for polymer solutions with an injection amount of 10m³/day, and different molecular weights and concentrations after the action of the partial pressure tool are shown in Figure 3.

As shown in Figure 3, the molecular morphologies of polymer solutions with different molecular weights and concentrations changed after the action of the partial pressure tool. The molecular chains were thinned or even broken, and the grid structure became looser. This is because the polymer solution was subjected to mechanical shearing as the solution flowed through the partial pressure tool. This shearing mainly resulted from the continuous changes in the flow cross section as the solution passed through the annular space. The mechanical shearing due to the sharp changes in the flow rate caused the appearance of defects in the network structure and the breaking of the molecular chains. The meshes hence became sparse. The ability of the network structure to encapsulate water molecules was greatly reduced, resulting in a significant reduction in adhesion. As the molecular weight increased, the polymer solution molecule deformation and the untwisting ability increased after the action of the partial pressure tool. The molecular chains were gradually thinned or even broken, and the grid structure became dispersed.

2.2.2. Influence of the Partial Pressure Tool on Polymer Solution Molecular Coils. The size of the molecular coils in the
polymer solution was measured by the dynamic light scattering method. The light scattering method is based on the optical inhomogeneity of the polymer solution, which is caused by the thermal movement of molecules in the medium and the resultant local stretching of the refractive index and dielectric constant. When light of a certain wavelength irradiates the particles, the frequency of the scattered light will undergo a Doppler shift. The magnitude of the shift is related to the motion speed of the particles. The translational diffusion rate $D$ of polymer molecules in the solution due to the Brownian motion can be determined by displacement measurements, and the molecular weight $M$ and hydrodynamic radius $R_h$ of the polymer can then be obtained from $D$. The dynamic light scattering instrument used in this research can directly measure the dynamic diameter $D_h$ (molecular coil size of the oil displacement system), which characterizes the degree of polymer chain curling and molecular coil size. For light scattering measurements of polymer solutions, dilute solutions are generally used, as the distances between molecules are relatively large, and external interference can be neglected. However, due to thermal motion, the conformations of the molecules change all the time, so the measured parameters are all statistical (Table 2).

A core with a permeability ratio of 3 and polymer solutions with different concentrations and molecular weights were selected for the displacement experiment at the low injection amount of $10^{-3}$/day.

By measuring the diameter of the molecular coils in polymer solutions with different concentrations and molecular weights and by considering the microstructure of the polymer solution discussed previously, the following was found: the length of the molecular chains, the complexity of the molecular conformations, the expansion of the polymer molecular chains, and the size $D_h$ of the polymer molecular coils measured by dynamic light scattering instrument all increased with the polymer molecular mass. In addition, in polymer solutions with a given concentration, increasing the polymer relative molecular mass lengthened the molecular chains and increased the charged groups contained in each molecular chain. This strengthened the total electrostatic repulsion force in the coil and enlarged the coil size.43

After the action of the partial pressure tool, the diameters of the molecular coils in polymer solutions with different concentrations and molecular weights were reduced by different degrees. The reduction resulted from the mechanical shearing action of the partial pressure tool on the polymer solution during the flow process, which changed the structure of the molecular chains and reduced the size of the molecular coils. With the increase of the polymer solution molecular weight, the reduction of the molecular coil size changed from 17.1 to 18.7% after the action of the partial pressure tool. However, with the increase of the polymer solution concentration, the reduction of the molecular coil size changed from 15.2 to 16.1% after the action of the partial pressure tool. This is a small change. Therefore, when the partial pressure tool is used to enhance the total oil recovery, changing the polymer solution concentration can reduce the degree of molecular structure change caused by the shearing action of the partial pressure tool and thus enhance the oil recovery to the greatest extent. This conclusion is consistent with the change trend of oil recovery with molecular micromorphology after the action of the partial pressure tool.

3. CONCLUSIONS

The effects of the partial pressure tool on enhancing oil recovery and its mechanism of action on polymer solution molecules were studied by core displacement and microscopic experiments. The following conclusions were obtained:

1. After the action of the partial pressure tool, the oil recovery from high-permeability cores was slightly reduced, while that from low-permeability cores was greatly increased. This shows that the total oil recovery is increased, the highest increase was 4.4%, and that the throttling pressure difference is directly proportional to the total oil recovery.

2. After the action of the partial pressure tool on high-permeability oil layers, the effect of changing the polymer solution concentration on enhancing oil recovery was

| molecular weight (x10$^3$) | concentration (mg/L) | molecular coil diameter before the action of the partial pressure tool (nm) | molecular coil diameter after the action of the partial pressure tool (nm) |
|---------------------------|-----------------------|-------------------------------------------------|-------------------------------------------------|
| 1600                      | 2000                  | 533                                             | 442                                             |
| 1900                      | 1500                  | 475                                             | 403                                             |
| 2000                      | 2000                  | 514                                             | 431                                             |
| 2500                      | 2000                  | 608                                             | 510                                             |
| 2500                      | 2000                  | 746                                             | 606                                             |

Figure 3. Scanning electron microscopy images of polymer solutions with different molecular weights and concentrations after the action of the partial pressure tool: (a) $1600 \times 10^3$, 2000 mg/L; (b) $2500 \times 10^3$, 2000 mg/L; (c) $1900 \times 10^3$, 1000 mg/L; (d) $1900 \times 10^3$, 1500 mg/L; and (e) $1900 \times 10^3$, 2000 mg/L.
greater than that of changing the polymer solution molecular weight.
3. The molecular structure of the polymer solution changed after the action of the partial pressure tool. The action of the tool thinned or even broke the molecular chains and loosened the grid structure, resulting in a decrease in viscosity. However, when the concentration of the solution was changed, the degree of the molecular structure change was small, and the effect on oil displacement was also small.
4. After the action of the partial pressure tool, the molecular coil size of the polymer solution decreased, but the change of the molecular coil size and the influence on the polymer properties were small when the concentration was changed.
5. When the partial pressure tool is used to enhance the oil displacement effect in heterogeneous reservoirs, a high-concentration polymer solution is more effective than a high molecular weight polymer solution in improving the total oil recovery, and leads to a smaller decrease in oil recovery from high-permeability reservoirs.

4. EXPERIMENTAL SECTION

4.1. Experiment Materials. 4.1.1. Cores. Experimental cores were provided by Daqing Oilfield Oil Production Engineering Research Institute. The permeability of the cores used are $100 \times 10^{-3}$, $300 \times 10^{-3}$, $600 \times 10^{-3}$, and $900 \times 10^{-3}$ μm² with a porosity of approximately 26%, oil saturation of approximately 72%, and core dimensions of 300 mm in length, 45 mm in width, and 45 mm in height.
4.1.2. Brine. Brine for the polymer solution preparation and formation brine for core saturation were provided by the Daqing Oilfield Oil Production Engineering Research Institute. Their compositions are shown in Table 3.
4.1.3. Experimental Oil. Oil for the core displacement experiments was provided by the no. 1 oil production plant of Daqing Oilfield. The viscosity of the oil is 7.95 mPa s at 45 °C.
4.1.4. Polymer Solution. The polymer used to prepare the polymer solution in this experiment is partially hydrolyzed polyacrylamide with relative molecular weights of 1600 × 10^3, 1900 × 10^4, and 2500 × 10^4. The degree of hydrolysis was approximately 23%. The polymer was provided by Daqing No. 1 Oil Production Plant.
4.1.5. Partial Pressure Tool. The model 306L partial pressure tool used in the experiment was provided by the Daqing Oilfield Oil Production Engineering Research Institute and is made of stainless steel. The total length of the tool used in the experiment is about 220 mm. Its annular throttling groove is composed of multiple throttling units. The structure and structural parameters of the tool are shown in Figure 4. The dimensions indicated in the figure are in millimeters.

The structure of the tool consists of an outer cylinder and an annular throttling groove. Polymer solution flows in the gap between the outer cylinder and the annular throttling groove. The crests and troughs of the annular throttling groove appear alternately in turn, as shown in Figure 4, resulting in periodic changes in the velocity and pressure of the fluid in the flow channel. These periodic changes generate strong disturbances in the velocity and pressure of the fluid and cause a large pressure drop when the polymer solution flows through the throttling groove.

4.2. Experimental Procedure. 4.2.1. Displacement Experiment of the Polymer Solution. The experimental setup for polymer flooding is shown in Figure 5. During the whole experiment, the operating temperature was maintained at 45 °C.

During the experiments, the core and the concentration and molecular weight of the polymer solution in piston container 1 were varied according to the experimental requirements, and formation brine was injected into piston container 2.

The partial pressure tool in the partial pressure injection distributor was installed or removed according to the experimental requirements. The cross section of the partial pressure injection distributor is shown in Figure 6.

The experimental process is as follows:

1. The cores with different permeabilities were numbered and recorded.
2. The cores were vacuumed for about 5 h.
3. The cores were saturated with formation brine, and the porosity was measured.
4. The cores were placed in an incubator and kept at 45 °C for 12 h.
5. The cores were saturated with oil until all the water was driven by oil to the model outlet, and no more water was produced.
6. The oil was displaced at a constant rate until the water cut at the outlet of the model reached 98% without the partial pressure tool in the partial pressure injection distributor to simulate the actual onsite water cut.
7. The polymer oil recovery in the displacement process was calculated and recorded.
8. The concentration and molecular weight of the polymer solution in piston container 1 were adjusted, and the core permeability was varied across different experiments.

Table 3. Brine Composition

| component       | NaCl | KCl | CaCl₂ | MgSO₄ | Na₂SO₄ | NaHCO₃ | total mineralization |
|-----------------|------|-----|-------|-------|--------|--------|---------------------|
| preparation brine (mg/L) | 736  | 374 | 401   | 146   | 109    | 118    | 1884               |
| formation brine (mg/L)    | 1368 | 602 | 268   | 173   | 164    | 206    | 2781               |
The partial pressure tool in the partial pressure injection distributor was installed and the above experimental steps repeated. When the measurements have stabilized, the pressures before and after the partial pressure tool was installed were recorded to obtain the throttling pressure difference.

The displacement process oil recovery was calculated and recorded.

Due to the low-permeability, thin oil layer thickness, and small injection volume (30–50 m³/day) in the entire well and the small injection volume (5–20 m³/day) in single layers of the three types of oil layers, it is necessary to use the partial pressure tool for layered injection in the high-permeability oil layers to increase the oil production in the medium- and low-permeability layers. Therefore, the injection volume of 10 m³/day was selected and maintained for the displacement experiments.

4.2.2. Characterization of the Molecular Microscopic Morphology of the Polymer Solution. The molecular morphology of the polymer solution was characterized by a scanning electron microscope (S-3400 N) by FEI company in the United States.

The experimental process of the molecular morphology characterization is as follows:

1. Sampling. A sampler was used to obtain polymer solution samples before and after the action of the partial pressure tool after the displacement experiment has stabilized.

2. Sample preparation. In order to truly reproduce the aggregation morphology of polymer molecules in the solution state, the freezing method was adopted. The samples were quickly transferred to a freezing table onto which liquid nitrogen at −70 °C was poured. The samples were vacuumized at the same time to sublimate and remove the water in the solution to obtain dry samples.

3. Coating. Samples for observation by a scanning electron microscope require conductivities of between $10^{-10}$ and $10^{-4} \, \Omega$ to prevent local charge accumulation on the samples from affecting the observation results. The prepared dry sample was placed in a high-voltage electric field with a certain degree of vacuum in which the high-voltage electric field ionized the air. A layer of a conductive metal film (gold) was then plated on the surface of the dry sample. Gold plating was carried out twice for 30 s each time.

4. Scanning with the electron microscope. The sample was taken out of the freezing chamber and directly moved into the scanning electron microscope, and observed in the sample chamber of the SEM. Typical areas were selected for photographing and aggregate structure analysis.

4.2.3. Characterization of the Polymer Solution Molecular Coil. The molecular coil size ($D_h$) of the polymer solution was measured by a Brookhaven BI-200SM wide-angle dynamic/static light scattering instrument system (Brookhaven Instruments Corp, USA). The main components include a BI-9000AT laser correlator and signal processor, an argon ion laser (200 mW, wavelength 532.0 nm) with the measurement scattering set to 90°, and a KQ3200DE numerical control ultrasonic cleaner.

The experimental process for the polymer solution molecular coil characterization is as follows:

(a) Experimental setup. 1, constant-flux pump. 2, piston container 1 (polymer solution). 3, piston container 2 (formation brine). 4, pressure gauge. 5, sampler. 6, partial pressure injection distributor. 7, core holder. 8, hand pump. 9, beaker. 10, core (high permeability). 11, check valve. 12, core (low permeability).

(b) Partial pressure injection distributor: (a) uninstalled and (b) installed.
(1) Sampling. The sampler was used to obtain polymer solution samples before and after the action of the partial pressure tool after the displacement experiment has stabilized.

(2) Filtering. The sample was filtered to remove dust by a nuclear microporous filter membrane with a diameter of 0.85 μm. The sample bottle containing the sample was cleaned for 5 min with the KQ3200DE numerical control ultrasonic cleaner.

(3) Dynamic light scattering measurement. The temperature of the thermostatic water bath was adjusted to 45 °C, and the sample bottle was put inside the scattering pool for measurement. The laser was turned on, and the diaphragm adjusted so that the scattered light intensity measured by the correlator fell inside the appropriate range. The measurement time for each sample was 2 min with a detection laser wavelength of 532.0 nm and a dynamic light scattering angle of 90°.

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Notes

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