INTRODUCTION

In water flooding oilfields, the injection water easily rushes or rapidly flows along high-permeable layers and through large core pores and cracks due to the heterogeneity of underground reservoirs and the viscosity difference between oil and water. Long-term washout of the injection water will aggravate the heterogeneous deterioration of reservoirs by easily forming favorable water flow paths in high-permeable zones of the formation. As a result, most of the injection
water rapidly flows along the favorable paths, leading to inefficient and void circulation. However, a number of undeveloped reservoirs or low-working-degree reservoirs still exist in the medium- and low-permeable layers of reservoirs. Moreover, abundant injection water and formation water are ineffectively produced, which increases energy consumption during production, pipeline corrosion, and sewage treatment costs and causes environmental pollution. Profile control is one of the most effective methods to improve the development effect and oil recovery of highly heterogeneous reservoirs in the high-water-cut stage by using chemical agents and related technology. However, as the reservoir structure becomes increasingly complex after entering the high- or ultrahigh-water-cut stage, the existing general profile control technology hardly meets the actual needs of reservoirs. To better exploit the potential of residual oil in low-permeable layers, researchers have developed various deep profile control techniques, such as colloidal dispersion gels (CDGs), preformed particle gels (PPGs), polymer microspheres, and inorganic gel coatings. CDGs are a gel system that relies on intramolecular crosslinking between a polymer and crosslinking agent. With the delayed crosslinking technique, CDGs can selectively enter high-permeability layers and thus effectively ease interlayer cross-flow. However, due to the very low gel strength, CDGs cannot control the reservoir sections in cracked, large-pore, and ultra-high-permeable layers. Additionally, the sensitivity to high temperature and high salinity limits the application of CDGs in oil reservoirs under harsh conditions. Traditional PPGs avoid the ungluing or low gel strength of underground crosslinking systems and can contribute to gel systems to the largest extent. However, due to the large particle sizes and irregular shapes, PPGs can block reservoirs and are ineffective in depth profile control. Thus, PPGs are often used to block high-permeable layers and fissures. Compared with organic profile control agents, inorganic gel coatings possess a higher heat resistance, salt resistance, and sealing performance, but the viscosity of injection liquids containing inorganic gel coatings is similar to that of water, which easily pollutes low-permeability oil zones of reservoirs. Moreover, blockage by inorganic sediments can be hardly handled, which will cause irreversible damage to reservoirs. Polymer microspheres are an emerging and promising deep profile control technology. Polymer microspheres, which are polymerized from a polymer monomer, a crosslinking agent, an initiator, and an active agent, can be prepared directly from wastewater and rarely pollute strata. Polymer microspheres have outstanding temperature resistance, salt resistance, and shear resistance. Polymer microspheres effectively avoid the defects and shortcomings of underground crosslinking systems, utilize gel systems to the largest extent, and have a high shut-off capacity. With modest deformability, microspheres can migrate into deep strata and directly adjust the nonuniformity of deep water flooding, which suggests a strong fluid diversion ability. At present, the deep profile control technology of polymer microspheres has been studied in the laboratory and successfully applied in the field to increase oil and decrease water production.

The migration law and mechanism of deep profile control by polymer microspheres in porous media have been studied extensively in recent years. Polymer microspheres can selectively shut-off rock core pores and block water flow without affecting oil flow. In rock pores, polymer microspheres can increase water flow resistance by blocking pore throats through adsorption, seizure, and bridging and thereby achieve the effect of liquid flow conversion. Polymer microspheres are elastic and can reach deep strata through elastic deformation and breakthrough, thereby achieving deep fluid diversion. Polymer microspheres have blocking-passing-blocking characteristics and can form pressure pulses in reservoirs, which promote the displacement of blind-end residual oil or surface-attached residual oil, enhancing oil recovery. The matching relationship between polymer microspheres and rock pores is a dominant factor affecting the profile control effect. The matching factor (ratio of rock core pore diameter to microsphere diameter) is used to characterize the matching relationship between polymer microspheres and rock pores. Traditional polymer microspheres achieve the best shut-off and deep fluid diversion effects only for a certain range of the matching factor. Researchers can controllably synthesize elastic microspheres based on sizes that match the pore throat sizes of reservoir rocks, thereby effectively improving the reservoir profile control effect and greatly increasing the oil recovery efficiency.

During the injection of polymer microspheres, the particle diameter and matching factor both change with the injection time. The matching factor has the best range only for a certain period. However, thus far, the matching factor, shut-off form, and deep-migration mechanism of polymer microspheres have been studied mostly with constant microsphere sizes or within short migration distances. The long-distance migration of polymer microspheres in porous media, the expansion, the shut-off form at different migration depths, and the deep-migration mechanism have not been systematically studied.

In this study, the dynamic migration law of polymer microspheres in reservoir pores was systematically studied by using an 18-m-long artificial rock core. The migration of polymer microspheres in porous media was divided into four periods according to the matching factor, resistance factor, residual resistance factor, and microsphere form in the migration process, and the best period was when the resistance factor and the residual resistance factor were the largest. Then, the deep profile control mechanism of polymer microspheres was further clarified by oil displacement experiments and characterization of the remaining oil saturation distribution. This study provides a scientific basis and technical support for further enhancing oil recovery by using polymer microspheres.
2 | EXPERIMENTAL CONDITIONS

2.1 | Materials

The HTPW-112 polymer (Oil Production Technology Research Institute, PetroChina Dagang Oilfield Company) used here featured a relative molecular weight of $2.5 \times 10^4$ and a solids content of 88.0%. The hydrolyzed polyacrylamide (HPAM) with a relative molecular weight of $1.9 \times 10^4$ and a solids content of 88.1% was provided by PetroChina Daqing. Self-made organic chrome ($\text{Cr}^{3+}$) with an effective content of 2.7% was used as the crosslinking agent. The polymer microspheres with an effective content of 100% used here were provided by the Research Institute of Petroleum Exploration Development.

Formation water of the Daqing Oilfield and simulated injection water were used here with the compositions shown in Table 1. Simulated oil with a viscosity of 9.8 mPa·s at 45°C was mixed from Daqing Oilfield dehydrated oil and kerosene.

2.2 | Physical model

The 18-m-long core was composed of two joined artificial cores consisting of clay-free quartz sand with geometric dimensions of $12.5 \times 63.5 \times 63.5 \text{ cm}^3$ (height × width × length). Ten pressure-measuring taps were distributed evenly along the core in the displacement direction, including $P_1$ (inlet), $P_2$, $P_3$, $P_4$, $P_5$, $P_6$, $P_7$, $P_8$, $P_9$, and $P_{10}$, which were 0, 1.8, 3.6, 5.4, 7.2, 9.0, 10.8, 12.6, 14.4, and 16.2 m, respectively, away from the inlet. Figure 1 shows the manufacture process of the physical model, including the following steps. (a) Two 60 cm × 60 cm × 4.5 cm artificial rock cores were pressed together; (b) the two rock cores were slotted as shown in the figure; (c) the lower core was put into a mold and cast with epoxy resin; (d) the upper core was
put into the mold on top of the lower as-cast core, and the upper core was cast with epoxy resin; (e) after the epoxy resin had cemented and solidified, the whole model was turned over, and the model bottom was cast with epoxy resin; (f) as the epoxy resin cemented and solidified, the model was turned over again, and the measuring points were perforated. At \( P_6 \), the holes penetrated into the lower core and functioned as a flow channel to connect the two rock core pieces. The pore depth was 2.25 cm at the other measuring points.

Figure 2 shows the internal flow system and core sections of the 18-m-long core. The 18-m-long rock core was divided into 10 sections, and the permeability of each section was measured. With \( P_1 \) as the inlet and \( P_2 \) as the outlet, the permeability of section 1 was measured; then, with \( P_2 \) as the inlet and \( P_3 \) as the outlet, the permeability of section 2 was determined, and so on. The parameters of each section are listed in Table 2.

### 2.3 Properties of the polymer microspheres

#### 2.3.1 Particle diameter

The particle diameters of the polymer microspheres in solution were tested by a laser particle analyzer (Zetasizer 1000HS/300HS, HORIBA LA300). The micromorphology was examined by a stereomicroscope (Carl Zeiss SteREO Discovery V12). The preparation process of the polymer microspheres in oil is illustrated in Figure 3. In brief, (a) 300 mL polymer microsphere solution was prepared using injection water, stirred for 30 minutes, and divided into three equal portions. (b) The first portion was used to test the particle diameter and the microsphere distribution in the solution and examine the micromorphology. (c) Then, 10 mL of the second portion was injected into a U-shaped tube from the inlet with syringe A, followed by the injection of kerosene with syringe B, which slowly progressed so that the oil-water interface dropped below the filter membrane with a pore diameter of 0.8 μm. At this time, the polymer microspheres in the solution were filtered by the filter membrane with a pore diameter of 0.8 μm. The ends of the U-shaped tube were sealed, and the tube was put into a constant-temperature box at 45°C for 72 hours and then taken out to determine the particle diameter and microsphere distribution. (d) The third portion was sealed and put into the constant-temperature box at 45°C for 72 hours, followed by particle diameter and microsphere distribution testing.

#### 2.3.2 Mechanical shear resistance performance

The polymer microsphere solution was tested at different times using a high-shear dispersing emulsifier machine (FLUKO FM200A) at a rate of 10^4 rpm. Before and after shearing, the average particle size of the polymer microspheres was measured by a laser particle size analyzer.

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**TABLE 2** Core parameters of the different model sections

| Scheme | Water-based permeability of the different sections (×10^{-3} μm²) | Average permeability (×10^{-3} μm²) | Pore diameter (μm) | Porosity (%) |
|--------|---------------------------------------------------------------|------------------------------------|------------------|-------------|
| 1‐1    | 2120.3 2118.1 2118.4 2120.9 2121.3 2122.4 2108.9 2126.7 2119.9 2114.4 | 2127.1 2119.9 | 33.7 | 21.28 |
| 1‐2    | 2113.3 2139.1 2112.8 2108.1 2125.5 2119.5 2138.4 2132.8 2126.2 2125.2 | 2125.2 2120.2 | 33.7 | 21.31 |
| 1‐3    | 2092.8 2091.8 2091.8 2087.9 2085.3 2087.4 2074.8 2070.7 2008.7 2004.8 | 2075.4 2075.4 | 33.7 | 21.13 |
| 1‐4    | 2155.1 2163.3 2169.9 2171.6 2166.3 2144.6 2164.7 2158.1 2157.2 2159.9 | 2158.1 2157.2 | 33.7 | 21.38 |
| 1‐5    | 2158.5 2142.7 2161.5 2154.7 2135.5 2158.6 2146.6 2137.9 2145.1 2149.7 | 2149.7 2145.1 | 33.7 | 21.40 |
| 1‐6    | 2075.1 2077.8 2061.2 2063.1 2079.2 2080.5 2078.9 2079.2 2075.1 2079.2 | 2075.1 2075.1 | 33.5 | 21.09 |
| 2‐1    | 2096.3 2092.9 2084.9 2110.9 2086.0 2078.4 2076.1 2070.7 2070.7 2075.1 | 2075.1 2075.1 | 33.6 | 21.15 |
| 2‐2    | 2141.2 2125.8 2136.0 2129.1 2120.2 2128.5 2135.2 2131.3 2137.7 2137.7 | 2137.7 2137.7 | 33.8 | 21.52 |
| 2‐3, 2‐4, 2‐5 | 2117.8 2112.5 2124.5 2114.1 2111.2 2112.8 2124.5 2124.4 2124.4 2124.4 | 2124.4 2124.4 | 33.7 | 21.28 |
(Zetasizer 1000HS/300HS, HORIBA LA300), and the micromorphology was examined under a stereomicroscope. The mechanical shear resistance of the microspheres was characterized by the particle size remaining degree:

\[
\text{Particle size remaining degree} = \frac{D_t}{D_0} \times 100\%
\]  

(1)

where \(D_0\) and \(D_t\) are the average microsphere particle size before and after shearing, respectively.

2.3.3 | Rheology

The rheological properties were determined using an RS-150 rheometer (HAAKE).

2.3.4 | Elasticity

The liquid was injected via Scheme 1-4, and the produced liquid was collected. The excessive water in the polymer microsphere solution was filtered out using filter paper, and then, the elastic modulus of the polymer microspheres (without the solvent) was detected by an Anna Par MCR302 rheometer. The procedures were as follows: (a) Strain sweep tests were conducted at an oscillation frequency of 1 Hz, which returned the grain strain to the linear viscoelastic zone, and (b) frequency scanning tests were conducted within this strain range to study the variation in the elastic modulus with the frequency.

2.4 | Matching relation between the particle diameters of the polymer microspheres and core pores

The matching relation between the polymer microspheres and core pores is represented by the matching factor:

\[
R_a = \frac{D}{d} = d^{-1} \left( \frac{72 k}{\phi} \right)^{0.5} \left( f_{\text{CK}} \tau^2 = 4.5 \right),
\]  

(2)

where \(D\) is the average diameter of the rock pore throats (μm), \(d\) is the average particle size of the polymer microspheres (μm), \(k\) is the absolute permeability (μm²), \(\phi\) is the porosity (%), \(f_{\text{CK}}\) is the Carman-Kozeny shape factor, and \(\tau\) is the tortuosity.

2.5 | Resistance factor and residual resistance factor

The resistance factor \(F_R\) and residual resistance factor \(F_{RR}\) are technical indicators that evaluate the ability of a chemical agent to ameliorate the mobility ratio and decrease the permeability of oil reservoirs:

\[
F_R = \frac{\delta P_2}{\delta P_1} \quad \text{and} \quad F_{RR} = \frac{\delta P_3}{\delta P_1}
\]  

(3)

where \(\delta P_1\), \(\delta P_2\), and \(\delta P_3\) are the differential pressures under water flooding, chemical flooding, and subsequent water flooding, respectively. During the injection process above, the injection rate must be kept the same and the liquid injection amount must be 4-5 pore volumes (PVs). In summary, (a) the saturated formation water core was drawn from the core, the simulated water was injected, and \(\delta P_1\) was recorded. (b) The chemical agent was injected up to 4-5 PVs, and \(\delta P_2\) was recorded. (c) Subsequent water flooding of 4-5 PVs was performed, and \(\delta P_3\) was recorded. (d) The particle diameter of the polymer microspheres in the produced liquid from each core was tested.

The 18-m-long core was divided into 10 sections, and the resistance factor and residual resistance factor of the chemical agent in each section were measured to study the retention capacity of the chemical agent in the strata at different displacement depths (Figure 4).

Scheme 1-1: At an injection rate of 0.5 mL/min, the resistance factor \(F_R\) and residual resistance factor \(F_{RR}\) of the polymer solution were tested in sections 1-10 of the 18-m-long core. The produced liquid from each section during chemical flooding was collected, and the molecular aggregate dimension of the polymer was measured with a Brookhaven BI-200SM dynamic/static light-scattering system (Brookhaven Instruments Corp.).
Schemes 1-2 to 1-4: At injection rates of 0.5, 1.0, and 1.5 mL/min, $F_R$ and $F_{RR}$ of the polymer microsphere solution were tested in sections 1-10 of the core.

Scheme 1-5: At an injection rate of 1.5 mL/min, $F_R$ of the polymer microsphere solution was tested in sections 1-10 of the 18-m-long core. Columnar cores were drilled from sections 1, 4, and 6 and were pressed, followed by examination of the microsphere forms under a stereomicroscope.

Scheme 1-6: At an injection rate of 2.0 mL/min, $F_R$ and $F_{RR}$ in sections 1, 2, 3, and 4 were determined. At an injection rate of 2.0 mL/min, the produced liquid from section 4 was collected and injected into point $P_5$ in section 5 at an injection rate of 0.5 mL/min; $F_R$ and $F_{RR}$ of the polymer microsphere solution were determined in sections 5-10.

The polymer microsphere solution was prepared with polymer microspheres and injection water with a mass concentration of 0.3%.

This solution was injected immediately after preparation and reprepared every 2 hours to ensure that the degrees of hydration and expansion were low before entering the core.

2.6 | Oil displacement experiments

The main devices of the displacement experiments included an ISCO pump, a pressure sensor, and a middle container. The ISCO pump remained at room temperature, while the other devices were in a thermostat oven at 45°C. The experimental circuit is shown in Figure 5. In brief, (a) the core was placed under vacuum and saturated with water, and the volume of saturated water was recorded. (b) The core was saturated with oil, the volume of saturated oil was recorded, and the oil saturation was calculated. The core was placed
under reservoir conditions for 24 hours. (c) Water flooding, chemical flooding, and subsequent water flooding were conducted. (d) The pressure and water cut were recorded during displacement, and the oil recovery was calculated. (e) The resistivity of each core section at the end of water saturation, oil saturation, water flooding, chemical flooding, and subsequent water flooding was recorded, and the remaining oil saturation was calculated.

Schemes:

Scheme 2-1: Water flooding was conducted to a water cut of 98%, 0.3 PV of the polymer solution was injected, and subsequent water flooding was performed to a water cut of 98%.

Scheme 2-2: Water flooding was conducted to a water cut of 98%, 0.3 PV of the polymer solution was injected, and subsequent water flooding was performed to a water cut of 98%. Then, 0.3 PV of the polymer gel was injected, and subsequent water flooding was conducted to a water cut of 98%.

Scheme 2-3: Water flooding was conducted to a water cut of 98%, 0.3 PV of the polymer solution was injected, and subsequent water flooding was performed to a water cut of 98%. Then, 0.3 PV of the polymer microsphere solution that had stood for 3 days after preparation was injected, and subsequent water flooding was conducted to a water cut of 98%.

Scheme 2-4: After the displacement of Scheme 2-1, 0.3 PV of the polymer microsphere solution was injected immediately after preparation, and subsequent water flooding was conducted to a water cut of 98%.

Scheme 2-5: After the displacement of Scheme 2-4, 0.3 PV of the polymer microsphere solution immediately after preparation was injected at a rate of 1.5 mL/min, and subsequent water flooding was conducted at an injection rate of 0.5 mL/min to a water cut of 98%.

The polymer solution was prepared with HTPW-112 polymer and injection water with a polymer concentration \( C_p = 2000 \text{ mg/L} \).

The polymer gel solution was prepared with HPAM (relative molecular weight of \(1900 \times 10^4\), \( C_p = 2000 \text{ mg/L} \)), and the mass concentration of the crosslinking agent was 1%.

The polymer microsphere solution was prepared with polymer microspheres and injection water with a mass concentration of 0.3%.

Before the experiment, the polymer solution was sheared to retain 60% of its viscosity, and the chemical agent was sheared before injection at this strength level. The injection rate was 0.5 mL/min except when specifically mentioned otherwise.

## 2.7 Oil saturation

Usually, the reservoir matrix is nonconductive, and the electrical conductivity is vastly different between water and oil. The electrical resistivity of crude oil is close to infinity (which is \(10^{-11} \Omega \text{ m}\)) and that of water is reversely associated with the salinity. Formation resistivity is mainly affected by the pore medium shape, the water salinity, and the oil-to-water ratio. When the medium porosity and water salinity remain unchanged, the resistivity is only related to the proportions of oil and water. Therefore, the change in oil saturation can be determined by the resistivity variation at both core ends.

The device was composed of a microelectrode, a transmission cable, and a data collector. The electrode detection points were located near the pressure-measuring points in the core, which were distributed at equal distances of 1.8 m along the streamline direction. Electrodes were inserted into the model before pressing and vertically located in the middle of the core. Then, the electrodes were arranged and cable-welded. The electrodes at the two ends of each section were used, and the resistance was obtained.

## 3 RESULTS

### 3.1 Polymer microsphere performance

#### 3.1.1 Particle size

The polymer microsphere solution was prepared with injection water and stood in water and oil separately for 3 days. The distribution of the particle diameters is shown in Figure 6. The polymer microspheres were expansive in water and nonexpansive in oil. At the beginning of solution preparation, the particle diameter of the polymer microspheres varied between 1 and 10 μm and was distributed mainly between 3.0
and 3.5 μm with a highest frequency of 25.9% and average particle diameter of 3.27 μm (Figure 6A). After standing in water for 3 days, the particle diameter of the polymer microspheres varied between 10 and 80 μm and was distributed mainly between 20 and 25 μm with a highest frequency of 25.2%, average particle size of 26.92 μm and expansion multiple of 8.23 (Figure 6B). After standing in oil for 3 days, the particle diameter of the polymer microspheres was 3.45 μm, and almost no expansion had occurred compared with the beginning of solution preparation (Figure 6C). Therefore, polymer microspheres entering high-water-cut layers expanded in water, which increased the flow resistance of the water phase and played a role in liquid diversion. Polymer microspheres entering oil layers no longer expanded, which minimized the pollution to the oil layer and was conducive to the development and recovery of the remaining oil.

3.1.2 | Mechanical shear resistance

The relationship between the particle size remaining degree of the polymer microspheres and shearing time was tested under different hydration time conditions, and microphotographs of the polymer microspheres were taken (Figure 7). Clearly, at the same hydration time, the particle size remaining degree of the polymer microspheres declined with prolonged shearing time (Figure 7A). At the same shearing time, the particle size remaining degree significantly declined, and the particle sizes of the polymer microspheres became enlarged with prolonged hydrated expansion time. Under shearing action, the large-sized polymer microspheres cracked and fractured (Figure 7B), indicating that the decline in particle size remaining degree was mainly caused by fragmentation of the large-sized microspheres. Polymer microspheres are three-dimensional network structures composed of chemical crosslinking and macromolecular interchain physical crosslinking. After expansion upon imbibing water, their macromolecular networks are expanded accordingly, and the crosslinking density and tangling degree are reduced, which weakens the strength of the polymer microspheres. Therefore, polymer microspheres with short expansion times possess excellent mechanical shear resistance.

3.2 | Resistance factor and residual resistance factor of different chemical reagents

At an injection rate of 0.5 mL/min, the resistance factor, residual resistance factor, and produced fluid molecular aggregate size remaining degree of the polymer microspheres were monitored.
dimension of the polymer solution in different core sections (Scheme 1-1) are shown in Figure 8. Clearly, the molecular aggregate dimension of the polymer and the resistance factor and residual resistance factor of the polymer solution all decreased with increasing displacement depth. At the beginning of injection, the polymer molecules with large molecular aggregate dimensions were captured more by the rock throat paths and were more resistant to the subsequent water flooding, so the chemical flooding injection pressure, the subsequent water flooding injection pressure, the resistance factor, the residual resistance factor, the fluid control ability, and the retention ability were all very high. After persistent shearing by the strata, the polymer molecular aggregate dimensions were destroyed, and the ability to be captured by rock throats and the ability against subsequent water flooding were weakened; thus, the chemical flooding injection pressure, the subsequent water flooding injection pressure, the resistance factor, the residual resistance factor, the fluid control ability, and the retention ability all decreased.

The resistance factor, the residual resistance factor, the produced fluid particle sizes, and the matching factor of the polymer microspheres in the different core sections (Scheme 1-2) are shown in Figure 9. With the increase in displacement depth, the particle sizes of the polymer microspheres first increased and then decreased, the matching factor first declined and then increased, while the resistance factor and residual resistance factor both first increased and then decreased. At the beginning of injection, the polymer molecules with small sizes had large matching factors, so the chemical flooding injection pressure, the subsequent water flooding injection pressure, the resistance factor, the residual resistance factor, the fluid control ability, and the retention ability were all very low. As time went on, polymer microspheres moved and expanded in the core pores, and the particle diameter, resistance factor, residual resistance factor chemical flooding injection pressure, and subsequent water flooding injection pressure all increased, but the matching factor decreased. In section 3 of the core, the injection pressures, resistance factor, and residual resistance factor were all at their maximum values. After section 4, the shearing action of the core on the polymer microspheres was more notable, and the injection pressure, resistance factor, and residual resistance factor all decreased.

The relationships between the injection pressure and PV injected of the polymer solution and the polymer microspheres in the different sections are shown in Figure 10. Clearly, the hydraulic pressure of the polymer solution was higher in section 1, similar in section 2, and lower in sections 3-10 compared with that of the polymer microspheres.

In summary, unlike the polymer solution, the polymer microspheres can reach an optimal mobility control and retention ability in the middle section of the core, which is valuable for further improving the oil recovery of reservoirs after the implementation of polymer flooding.

### 3.3 Migration characteristics of the polymer microspheres

#### 3.3.1 Resistance factor and residual resistance factor

The relationships of the resistance factor, residual resistance factor, particle size, or matching factor of the polymer microspheres with the displacement depth at an injection rate of 0.5 mL/min (Scheme 1-4) are shown in Figure 11. The relationships between the injection pressure and PV injected of the polymer microspheres in the different sections are shown in Figure 12. Clearly, as the displacement depth increased,
the particle sizes of the polymer microspheres in the produced fluids first increased and then declined, but the matching factor first decreased and then increased. Moreover, with increasing displacement depth, the resistance factor (or chemical flooding pressure) and residual resistance factor (or the subsequent water flooding pressure) first increased and then decreased (Figures 11 and 12).

### 3.3.2 Rheology

The rheological properties of the produced fluids from sections 1, 4, 6, and 10 in Scheme 1-4 are shown in Figure 13. Clearly, the apparent viscosity of the produced liquids from the polymer microspheres was affected by the migration depth. Before section 6, the particle sizes of the polymer microspheres and the apparent viscosity of the produced liquids both increased with increasing migration depth (Figure 11). After section 6, long-distance shearing of the rock core led to fragmentation of the polymer microspheres, which reduced the apparent viscosity of the microspheres.
Moreover, at a low shear rate (<170/s), the apparent viscosity of the polymer microsphere solution decreased with increasing shear rate, which indicated a pseudoplastic fluid. At a medium shear rate (170‐500/s), the apparent viscosity of the injected liquid and the produced liquids in sections 1, 4, and 6 all increased with increasing shear rate, which indicated dilatant fluids. The apparent viscosity of the produced liquids from section 10 was basically unaffected by the shear rate, which was close to a Newtonian fluid. At a high‐shear rate (500‐1000/s), as the shear rate increased, the apparent viscosity of the polymer microsphere solution was almost constant, which reflected the properties of a Newtonian fluid. This phenomenon occurred because the shear rate was below the critical shear rate (the shear rate at which a system transitions from shear thinning to shear thickening), and the overall crosslinked polymer microsphere scattered system was manifested as a stratified orderly structure. The microsphere particles flowing in separate layers were mutually independent, and the shear force was deformed and oriented to a limited degree only in the individual layers, which manifested as shear thinning. Above the critical shear rate, the system turned from a stratified orderly structure into a disorderly structure. Moreover, the presence of crosslinked points between the microspheres inhibited microsphere deformation, and the microspheres did not linearly stretch to a large extent and instead were connected to form particle aggregates via intermolecular forces or via intermolecular hydrogen bonding between amide groups of the polymer molecules and water molecules, leading to shear thickening. However, the shear stress can also break off aggregates while promoting the formation of particle aggregates. When the aggregate formation ability of the shear stress surpassed the aggregate separation ability, the fluid became a dilatant fluid; when the shear rate was enhanced to a certain level, particle aggregate formation and aggregate separation were in a dynamic balance, and the apparent viscosity of the system was basically unaffected by the shear rate, which was approximately a Newtonian fluid. The produced liquid from section 10 remained subjected to shearing for a long time, and the inner structure of the polymer microspheres was destroyed, forming particles with a low clustering ability; thus, dilatant properties were not observed.

3.3.3 | Elasticity

The elastic modulus, also called the storage modulus, reflects the amount of energy stored in the microspheres with elastic deformation under the shaking mode and can characterize the elasticity magnitude of the polymer microspheres. The elastic moduli of the injection fluid and the produced fluids of polymer microspheres (without solvent) from sections 1, 4, 6, and 10 in Scheme 1‐4 are shown in Figure 14. Clearly, as the migration time of the microspheres in the core was prolonged, their hydrated expansion ability and core shear action were enhanced, and the inner structure of the microspheres was further destroyed, leading to a reduction in the elastic modulus of the microspheres.

3.3.4 | Form of the microspheres in the porous media

Columnar cores were drilled from sections 1, 4, and 6, and the forms of the polymer microspheres in the columnar cores are shown in Figure 15. Clearly, the flow mode of the polymer microspheres in the porous media was a suspended disperse flow of abundant spherical small particles. In section 1, the microspheres had small diameters and were carried by fluids flowing through the large‐pore canals (Figure 15A). As the time of movement in the core pores was prolonged, the
microspheres expanded, and multiple microspheres blocked the pore surfaces and pore throats of the porous media (Figure 15B). Zhao et al reported a similar phenomenon by using scanning electron microscopy.39 As the time of movement in the core pores was further prolonged, the microspheres further expanded, and single microspheres were retained in the core pore throats (Figure 15C). Under extrusion by the driving force of the fluid and the pore throat walls, the microspheres retained in the pore throats were physically shut-off, and their movement was deformed; thus, they were separated from the pore surface and carried by the flowing fluids to further migrate.

3.3.5 | Migration characteristics of the microspheres

Based on the above experimental results, the migration of polymer microspheres was divided into four periods from the injection end to the production end, including transportation, bridging plugging, elastic plugging, and fatigue (Figure 16).

1. Transportation period. The polymer microspheres migrated through section 1 of the core and had a small resistance factor and low injection pressure. The diameters of the polymer microspheres at the injection end and the production end varied between 3.37 and 8.62 μm, while \( R_a \) ranged from 6.36 to 2.49 (Table 3). At this moment, most of the microspheres had passed through the core pores smoothly and no effective plugging occurred (Figure 15A).

2. Bridging plugging period. The polymer microspheres migrated through sections 2-4, and their resistance factor and injection pressure increased notably compared with the transportation period. According to the tests of the produced liquids at the ends of sections 1-4, the particle diameter of the polymer microspheres in the produced liquids ranged from 8.62 to 19.84 μm, and \( R_a \) ranged from 1.08 to 2.49 (Table 3). The particle diameters of the polymer microspheres in the produced liquids at the ends of sections 2, 3, and 4 ranged from 8.62 to 13.83 μm, 13.83 to 17.22 μm, and 17.22 to 19.84 μm, respectively, and the corresponding \( R_a \) ranged from 2.49 to 1.55, 1.55 to 1.25, and 1.25 to 1.08, respectively. During this period, the microspheres in the porous media were dominated by bridging plugging (Figure 15B). If the core pore throats were approximately considered as circles, bridging plugging can be divided into 2-, 3-, 4-, and multiparticle plugging (Figure 16), and the maximum \( R_a \) to realize plugging was 2, 2.15, and 2.41, respectively. At the beginning of bridging plugging, the particle diameter was small, the number of particles involved in plugging and \( R_a \) were large, but the plugging probability and resistance factor were small. With prolonged displacement time, multiparticle plugging gradually transitioned to 4-, 3-, and 2-particle plugging, while the plugging probability and resistance factor gradually increased. In sections 2-4, \( R_a \) decreased from 2.49 to 1.08, while the
plugging probability and resistance factor gradually increased. Because of the low probability of multiparticle plugging, 4-particle plugging was considered to be the limit of bridging plugging, or $R_a < 2.41$.

3. Elastic plugging period. The resistance factor and injection pressure of the polymer microspheres in section 5 and subsequent sections increased notably compared with the bridging plugging period. The particle diameters of the polymer microspheres at the end of section 4 to the end of section 6 ranged from 19.84 to 23.19 μm, and $R_a$ ranged from 1.08 to 0.92 (Table 3). In particular, the particle diameters in sections 5 and 6 varied from 19.84 to 21.77 μm and 21.77 to 23.19 μm, respectively, and the corresponding $R_a$ was from 1.08 to 0.98 and 0.98 to 0.92, respectively. At this moment, $R_a$ was <1, and the microsphere diameter was large. Single microspheres can plug core pore throats, elastic plugging occurred by microsphere deformation through core pores (Figure 15C). These results are consistent with other studies.37,39,45

4. Fatigue period. The polymer microspheres migrated through sections 7-10, and the resistance factor and injection pressure decreased compared with the elastic plugging period. At the end of section 7 to section 10, the polymer microspheres in the produced liquid were damaged and had entered the fatigue period (Table 3). After many cycles of elastic plugging, deformation breakthrough and form recovery, the recovery ability of the polymer microspheres was gradually weakened until shear failure occurred (Figure 11). As a result, the plugging ability declined, while the resistance factor and residual resistance factor decreased significantly.

In conclusion, polymer microspheres can migrate and expand simultaneously in porous media. With the increase in displacement depth, the particle diameter of the microspheres increases and $R_a$ decreases. The transportation, bridging plugging, elastic plugging, and fatigue periods corresponded to $R_a > 2.41$, $1 < R_a < 2.41$, and $R_a < 1$, and microsphere fracturing, respectively. During the whole migration process, the resistance factor and residual resistance factor of the polymer microspheres were relatively large in the bridging plugging and elastic plugging periods. Therefore, these two periods should be extended (through synthesis of polymer microspheres with a higher shear resistance), and their positions (distance from the injection end) should be adjusted reasonably to achieve deep profile control and oil displacement.

### 3.4 Effects of the injection rate on the migration of polymer microspheres

The breakthrough time, particle diameter, and matching factor of the polymer microspheres in the produced liquid are shown in Table 3. The particle diameter increased, and the matching factor $R_a$ decreased with prolonged displacement.
time before the breakage of polymer microspheres occurred. The elastic plugging period appeared when $R_a$ was smaller than 1. At injection rates of 0.5, 1.0, and 1.5 mL/min, the elastic plugging period appeared at displacement times of 23.5-46.5 hours, 34.5-46.5 hours, and 31-38.5 hours, respectively, and the corresponding $R_a$ values were 1.17-0.90, 1.01-0.91, and 1.08-0.98, respectively, corresponding to sections 2, 4, and 5, respectively, of the core in Figure 17.

At the different injection rates, the relations of the resistance factor and residual resistance factor with the displacement depth are shown in Figure 17. The relationships between the stable pressure and displacement depth in the chemical flooding and subsequent water flooding stages are shown in Figure 18. With the increase in injection rate, the distance from the injection end and the distance at which point the polymer microspheres entered the elastic plugging period increased. In addition, the accelerated injection rate increases the injection pressure, which contributes to profile control within a certain displacement depth. However, if the injection rate was too high, the shearing action of the cores on the microspheres was stronger, and consequently, the maximum resistance factor and residual resistance factor were smaller, which reduced the effective profile control depth of the polymer microspheres.

The relationships of the resistance factor and residual resistance factor with the displacement time at different injection rates are shown in Figure 19. The relationships between the stable pressure and displacement depth in the chemical flooding and subsequent water flooding stages are shown in Figure 20. The corresponding displacement time of the polymer microspheres entering the elastic plugging period was within 34.5-38.5 hours at injection rates of 0.5, 1.0, or 1.5 mL/min (Table 3). Therefore, 35 hours was selected as the time of the polymer microspheres entering the elastic plugging period (Figures 19 and 20). Clearly, the resistance factor (or residual resistance factor) before entering the elastic
plugging period was barely affected by the injection rates. After entering the elastic plugging period, both the resistance factor and residual resistance factor decreased with increasing injection rate, and the fatigue period appeared early. This result was because in the transportation period, the polymer microspheres had small particle diameters and were slightly affected by the shearing action of the core; thus, the shearing strength was slightly affected by the increasing injection rate. Then, in the bridging plugging period, the flow resistance intensified gradually with increasing particle diameter of the polymer microspheres, while the shearing action of the core on the polymer microspheres was enhanced and affected by the increasing injection rate. In addition, the probability of bridging plugging increased with increasing injection rate. Another reason for the reduced resistance factor was that at a high pressure, some of the particles involved in bridging plugging experienced shear failure. During the elastic plugging period, the particle diameter of the polymer microspheres further increased, and the microspheres migrated farther along with increasing injection rate, which also indicated more elastic deformation. The life of the microspheres was greatly shortened, bringing the fatigue period forward and causing a rapid drop in the resistance factor.

The injection rate in Scheme 1-6 was as follows: The injection rate increased to 2.0 mL/min in section 1 to section 4 of the core and decreased to 0.5 mL/min in section 5 to section 10. After the injection rate was changed, the polymer microspheres entered the elastic plugging period in Scheme 1-6 in section 5, which was the same as that at a constant injection rate of 1.5 mL/min in Scheme 1-4 (Figure 17). In addition, the maximum resistance factor and residual resistance factor in Scheme 1-6 were both larger than those at a constant injection rate of 1.0 mL/min in Scheme 1-3, and the effective profile control depth had increased. Therefore, a variable injection rate should be adopted to obtain the maximum resistance factor at a larger distance from the injection end and to keep the resistance factor at a high level. Namely, the injection rates in the transportation and bridging plugging periods should be increased to make elastic plugging occur at a larger distance from the core.
injection end, and the injection rate in the elastic plugging period should be decreased to weaken the shearing action of the core on the microspheres and to maintain the resistance factor at a high level.

The relationships between the injection pressure and PV injected in the different sections at different injection rates are shown in Figure 21. Clearly, during injection at a constant rate, the displacement distance corresponding to the maximum pressure \( P_{\text{max}} \) was longer with the increase in injection pressure. At injection rates of 0.5, 1.0, and 1.5 mL/min, \( P_{\text{max}} \) appeared at 5.4, 9.0, and 10.8 m away from the inlet, respectively. This result was mainly because the migration time needed by the polymer microspheres enter the elastic plugging period was not very different (34.5-38.5 hours), but the microspheres will be transported farther at a high injection rate, and elastic plugging occurred at the larger distance from the inlet. However, beyond a distance of 12.6 m from the inlet, the injection pressure of the polymer microspheres at varying injection rates was higher compared with the constant-rate injection pressure. This result further suggests that the appropriate adjustment of the injection rate can effectively enhance the ability of the polymer microspheres to displace deeper fluids.

### 3.5 | Mechanism of deep profile control

The increments in oil recovery improvement during polymer flooding, polymer microsphere flooding and polymer gel flooding are shown in Table 4. The viscosity of the polymer solution, the polymer gel, and the polymer microsphere solution at 45°C is 66.1, 127.5, and 1.3 mPa s, respectively.

The chemical agent type and the combination of injection segments both influenced the increasing amplitude of oil recovery (Table 4). With the oil recovery of polymer flooding in Scheme 2-1 (which was 57.2%) as the baseline, the incremental oil recovery values during polymer gel flooding in Scheme 2-2, swelling polymer microsphere flooding in Scheme 2-3, and polymer microsphere flooding in Scheme 2-4 were 4.4%, 1.0%, and 5.8%, respectively, and the maximum increment was found in Scheme 2-4. On the basis of Scheme 2-4, after the injection rate in the chemical flooding stage was increased, oil recovery could be further enhanced by injecting polymer microspheres again in Scheme 2-5, and the chemical flooding oil recovery can be enhanced from 63.0% to 67.1%.

The relationships between oil saturation and displacement depth at the end of water flooding and at the end of the first chemical flooding, the end of the second chemical flooding, and the end of the third chemical flooding are shown in Figure 22. The displacement depth, displacement mode, and chemical agent type all influenced the remaining oil saturation. The remaining oil saturation increased with increasing displacement depth, or namely, the distance from the injection end. The remaining oil saturation decreased remarkably after polymer flooding compared with water flooding, and the remaining oil saturation was higher at a further distance away from the injection end. The remaining oil saturation ranged from 20.1% to 21.4% within 5.4 m from the injection end, gradually increased at a distance beyond 5.4 m away from the injection end and reached 51.0% at the furthest point from the injection end. Therefore, the area of remaining oil accumulation after polymer flooding was located more than 5.4 m away from the injection end. Neither the polymer gel in Scheme 2-2 nor the swelling polymer microspheres in Scheme 2-3 had the capacity of deep fluid diversion, and after the remaining oil saturation of the injection end decreased to 20%, the decreasing range of the remaining oil saturation was limited. Therefore, the incremental oil recovery values were not large in Schemes 2-2 and 2-3. In Scheme 2-4, the polymer microspheres injected into the core immediately after preparation were capable of simultaneous migration and expansion, so that the profile control could start at the center of the core. The remaining oil saturation decreased remarkably from 9.0 to 12.6 m away from the injection end, and the oil recovery
### TABLE 4  Increments in oil recovery

| No. of Scheme | Scheme | Oil saturation (%) | Water flooding | Oil recovery | Increment in oil recovery (with baseline of 48.8\%) | Second chemical flooding (gel flooding or microsphere flooding) | Third chemical flooding (microsphere flooding) | Increment in oil recovery (with baseline of 63.0\%) | Increment in oil recovery (with baseline of 57.2\%) |
|---------------|--------|--------------------|----------------|-------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| 2-1           | Polymer + subsequent water flooding | 70.1               | 48.8           | 57.2        | 8.4                                             | —                                               | —                                               | —                                               | —                                               |
| 2-2           | Polymer + subsequent water + polymer gel + subsequent water flooding | 71.4               | 49.0           | 57.5        | 8.7                                             | 61.6                                           | 4.4                                             | —                                               | —                                               |
| 2-3           | Polymer + subsequent water + polymer microspheres (swelling) + subsequent water flooding | 71.8               | 49.3           | 57.8        | 9.0                                             | 58.2                                           | 1.0                                             | —                                               | —                                               |
| 2-4           | Polymer + subsequent water + polymer microspheres (nonswelling) + subsequent water flooding | 70.1               | 48.8           | 57.2        | 8.4                                             | 63.0                                           | 5.8                                             | —                                               | —                                               |
| 2-5           | Polymer + subsequent water + polymer microspheres (nonswelling) + subsequent water + polymer microspheres (nonswelling) + subsequent water flooding | 70.1               | 48.8           | 57.2        | 8.4                                             | 63.0                                           | 5.8                                             | 67.1                                           | 4.1                                             |

**Note:** According to the matching factor \( R_a \), resistance factor, and residual resistance factor, the migration of polymer microspheres in porous media was divided into four periods: transportation \((R_a > 2.41)\), bridging plugging \((1 < R_a < 2.41)\), elastic plugging \((R_a < 1)\), and fatigue (microsphere breakage).
increased by 5.8%. In Scheme 2-5, when the polymer microspheres were injected again at a high rate, the elastic plugging period was postponed, and profile control started at a farther distance from the injection end. The remaining oil saturation decreased again at 10.8-16.2 m away from the injection end, and the oil recovery increased by 4.1%.

In summary, the simultaneous migration and expansion characteristics of the polymer microspheres are the main mechanism of their deep fluid diversion effects. Since the area of remaining oil accumulation was far from the injection end, it was very important to select polymer microspheres with different expansion rates or adjust the microsphere injection rate in accordance with the actual situation in oilfields.

4 | CONCLUSIONS

The particle size distributions and mechanical shear resistance of polymer microspheres in water and oil were studied. Through mobility experiments, the migration law of polymer microspheres in an 18-m-long core was systematically studied according to the resistance factor and the residual resistance factor. The rheological properties of the produced liquids and the elasticity of the produced microspheres were examined, and the microsphere forms in porous media were observed. Through oil displacement experiments, the deep profile control mechanism of polymer microspheres in the 18-m-long core was studied according to the increasing range of oil recovery and the distribution characteristics of the remaining oil saturation.

1. Polymer microspheres were expansive in water and nonexpansive in oil. The polymer microspheres with a short expansion time possessed an excellent mechanical shear resistance.

2. As the displacement depth increased, the particle diameter of the polymer microspheres increased, and the matching factor decreased. The migration of polymer microspheres in porous media was divided into four periods: transportation ($R_a > 2.41$), bridging plugging ($1 < R_a < 2.41$), elastic plugging ($R_a < 1$), and fatigue (microsphere breakage).

3. The resistance factor and residual resistance factor of the polymer microspheres were larger in the bridging plugging and elastic plugging periods. Therefore, these two periods should be extended (through synthesis of polymer microspheres with a higher shear resistance), and their positions (distance from the injection end) should be reasonably adjusted to achieve deep profile control and better oil displacement.

4. The optimal profile control depth of oil displacement (distance from the injection end) of the polymer microspheres in porous media can be regulated by increasing the injection rate in the transportation and bridging plugging periods and by decreasing the injection rate in the elastic plugging period, thereby enhancing oil recovery.

5. The simultaneous migration and expansion of polymer microspheres is the main mechanism of deep microsphere fluid diversion in porous media.

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