

## Research Article

# Chemical Migration and Emulsification of Surfactant-Polymer Flooding

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With a long sand-packed core with multiple sample points, a laboratory surfactant-polymer flooding experiment was performed to study the emulsification mechanism, chemical migration mechanism, and the chromatographic separation of surfactant-polymer flooding system. After water flooding, the surfactant-polymer flooding with an emulsified system enhances oil recovery by 17.88%. The water cut of produced fluid began to decrease at the injection of 0.4 pore volume (PV) surfactant-polymer slug and got the minimum at 1.2 PV. During the surfactant-polymer flooding process, the loss of polymer is smaller than that of surfactant, the dimensionless breakthrough time of polymer is 1.092 while that of surfactant is 1.308, and the dimensionless equal concentration distance of the chemical is 0.65. During surfactant-polymer flooding, the concentration of surfactant controls the formation of the emulsion. From 50 cm to 600 cm, as the migration distance increases, the concentration of surfactant decreases, and the emulsification strength and duration decrease gradually. With the formation of emulsion, the viscosity of the emulsion is relatively stable, which is beneficial to enhanced oil recovery. With the shear of reservoirs and migration of surfactant-polymer slug, the emulsion is formed to improve the swept volume and sweep efficiency and enhance oil recovery.

## 1. Introduction

After water flooding, a large amount of oil is left in the oil reservoir, which is trapped in the pores by capillary forces. The main target of chemical flooding is the water-flooded residual oil. Chemical flooding has become the leading technologies for water flooded onshore oilfields to improve oil recovery in China. The alkali-surfactant-polymer flooding, polymer flooding, and surfactant-polymer flooding are most widely used [1]. Surfactant-polymer flooding not only avoids the scaling and corrosion of alkali-surfactant-polymer flooding but also improves the sweep efficiency of polymer flooding, which has a good application prospect [2, 3].

The polymer controls water-oil mobility that aqueous permeability is decreased, and the injected fluid does not bypass the displaced fluid. The surfactant will lower the

interfacial tension and decreases the capillary forces inside the pore [4]. Compared with polymer flooding and surfactant flooding, surfactant-polymer flooding can achieve significant improvements at a lower chemical concentration. Surfactant-polymer flooding can achieve ultralow interfacial tension and increase oil displacement efficiency, which could enhance oil displacement efficiency by 20% and decrease the injection pressure in low permeability reservoirs [5, 6].

In the process of surfactant-polymer flooding, several interactions between surfactant-polymer and reservoir fluids which will lead to the wettability alteration, adsorption to the rock, reduction of interfacial tension between water and crude oil, and the creation of an emulsion phase [7]. Due to these complex reactions, chromatographic separation occurs when surfactants and polymers migrate in porous media, and the loss of surfactant is more serious than polymer. The

chromatographic separation of polymer and surfactant affects the working distance of surfactant-polymer slug in reservoirs. The choice of surfactant and polymer for surfactant-polymer flooding is usually to achieve ultralow interfacial tension and control water-oil mobility [8]. However, the formation of an emulsion of microemulsion has a significant contribution to enhanced oil recovery of surfactant-polymer flooding.

In 1973, McAuliffe studied that injecting emulsion into a core can increase sweep efficiency [9]. Since then, the enhanced oil recovery of emulsions has been studied. The emulsion could increase the viscosity of the mobile phase to increase the swept volume, and the emulsifier can effectively emulsify the oil droplets [10, 11]. An emulsified system can enhance oil recovery by 5%–10% more than an unemulsified system [12, 13]. To heavy oil, the formation of emulsion could reduce the viscosity and improve flow capacity of heavy oil. Oilfield production results show that emulsion flooding can increase sweep efficiency and oil production of heavy oil [14].

The emulsion is unstable [15, 16], and it is relatively difficult to study the emulsification in an underground displacement process. At present, most studies focus on the migration and blockage mechanisms of emulsion [17, 18]. The emulsification of the chemical flooding is mainly simulated on small physical models [8, 19–21], so it cannot adequately reflect the migration and emulsification of the chemical slug underground.

The main objective of this work is to design a long core model with multiple sample points to simulate the process of surfactant-polymer flooding and simulate the process of chemical migration and emulsification. In the experiment, the recovery, chemical concentration, water cut, viscosity, and the emulsification process are analyzed.

## 2. Materials and Methods

**2.1. Chemicals and Materials.** Crude oil, hydrolyzed polyacrylamide (HPAM, the molecular weight of 10 million), and petroleum sulfonate (KPS, mean molecular weight: 380) was obtained from Block Qizhong, Xinjiang oilfield (Karamay, China). Quartz sand (80/240 mesh) and reagent-grade  $\text{MgSO}_4$ ,  $\text{NaCl}$ ,  $\text{CaCl}_2$ ,  $\text{NaHCO}_3$ , and  $\text{NaH}_2\text{PO}_4$  were purchased from Tianjin Dingshengxin chemical industry (Tianjin, China); HPLC-grade methanol and isopropanol were obtained from Damao chemical reagent factory (Tianjin, China); sulfonate column and polymer column were provided by Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences.

**2.2. Instrumentation.** An Agilent 1260 Infinity Quaternary high-performance liquid chromatography (HPLC) system, Electronic Balance YP30001, a ZEISS AXIO IMAGER fluorescent biomicroscope, a BROOKFIELD DV II-T viscometer, an ISCO syringe pump, an FY-31 thermostat were used in this study. As shown in Figure 1, a model composed of six  $100 \times 2.5$  cm sand-packed tubes (three straight tubes and three curved tubes) was built; sampling points were set

in the middle of each tube, and pressure sensors were connected. The distance between the sampling point and the injection well is 50 cm, 150 cm, 250 cm, 350 cm, 450 cm, 550 cm, and 600 cm, respectively.

**2.3. Core Experiment.** A sand-packed-tube core was prepared with quartz sand and model. The core parameters are shown in Table 1.

The parameters of simulated formation water are presented in Table 2.

The model was saturated with formation water and aged in the thermostat at  $40^\circ\text{C}$  for a week, and then the crude oil was saturated and aged in the thermostat at  $40^\circ\text{C}$  for another week. Based on the field injection rate of Qizhong Block of Xinjiang oil field (injection of surfactant-polymer slug: 1–2 m/d), water flooding was carried out at the flow rate of 0.12346 ml/min and stopped when the water cut of production fluid was higher than 98%; then, the recovery was figured out.

After the water flooding, 0.3% KPS with 1000 mg/L HPAM surfactant-polymer slug was injected. The total injection volume of the surfactant-polymer slug was 2.5 PV (including 0.5 PV sampling loss), and 3 ml of liquid was collected at each sampling point for each injection of 0.1 PV of surfactant-polymer solution.

At the end of surfactant-polymer flooding, a follow-up water flooding was carried out, the total volume of chase water was 1.2 PV (including 0.2 PV sampling loss), and 3 ml of liquid was collected at each sampling point for each injection of 0.1 PV of simulated water. The ultimate recovery, chemical concentration, viscosity, and the particle size of the emulsion of samples collected from different sampling points were detected and analyzed.

**2.4. Sample Detection.** All the sample collected in the core experiment was detected. The chemical concentration was detected by HPLC. The viscosity of emulsion was measured at  $40^\circ\text{C}$ . The particle size of the emulsion is detected by microscopy.

## 3. Results and Discussion

**3.1. Core Flooding Experiment.** As shown in Figure 2, during the water flooding process, about 1.355 PV formation water was injected to the core, and the recovery increased rapidly with the increase in water injection; when the injection water broke through, the water cut increased sharply to more than 80% and continued to increase, the recovery increased slowly and was about 48.93% at the end of water flooding.

During the surfactant-polymer flooding process, the water cut began to decrease after 0.4 PV surfactant-polymer slug was injected. With the injection of the surfactant-polymer solution, the water content continued to decrease and get the minimum at 61.4% when 1.2 PV surfactant-polymer slug was injected. At the end of the surfactant-polymer flooding, the water cut reached 93%. The recovery during surfactant-polymer flooding and follow-up

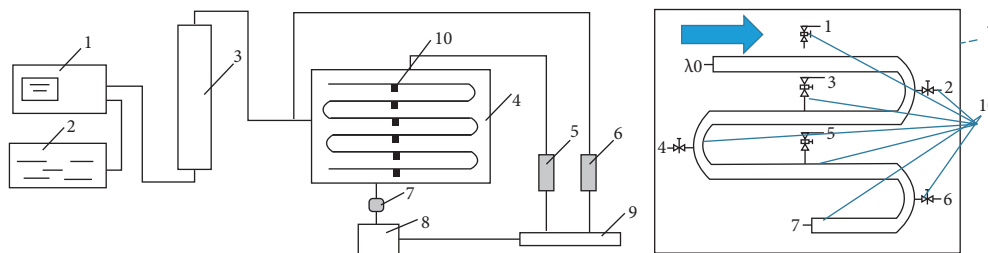


FIGURE 1: Emulsification experimental apparatus based on a long core. 1, ISCO pump; 2, simulated water; 3, intermediate container; 4, the physical model; 5, 6, and 7, pressure sensors; 8, computer; 9, data acquisition system; 10 sampling points.

TABLE 1: Parameters of sand packed core.

Parameter	Length (cm)	Diameter (cm)	Pore volume (ml)	Porosity (%)	Saturated oil (ml)	Water permeability (mD)	Oil saturation (%)
Values	600	2.5	888.926	30.19	643.3	184.01	72.37

TABLE 2: Ionic content of simulated formation water from Block Qizhong, Xinjiang.

Ionic composition	HCO <sub>3</sub> <sup>-</sup> (mg/L)	Cl <sup>-</sup> (mg/L)	SO <sub>4</sub> <sup>2-</sup> (mg/L)	Ca <sup>2+</sup> (mg/L)	Mg <sup>2+</sup> (mg/L)	Na <sup>+</sup> K <sup>+</sup> (mg/L)	Salinity (mg/L)
Concentration	762.75	1063.59	114.1	28.6	19.3	1023.27	3011.61

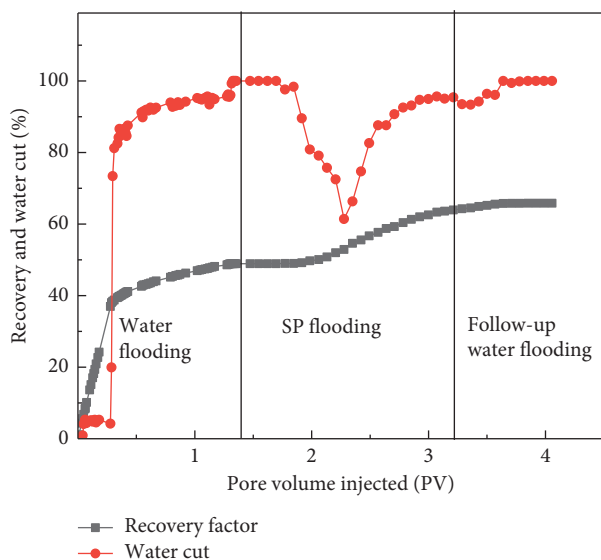


FIGURE 2: Recovery and water cut of pore experiment.

flooding was 17.88% (the lost oil volume at sampling points accounted for 16.75% of total saturated oil volume).

After the injection of surfactant-polymer slug, water cut varies significantly at different positions. Figure 3 shows the variation of water cut at each point after the injection of the surfactant-polymer slug. The water cut at each point decreased to various degrees, the overall water cut decreased by 21% at the production well of the core (600 cm), and the water cut decline was the most obvious at 150 cm and 550 cm from the injection well, as high as 100% and 77%, respectively. The change of water cut showed that an oil bank was formed in the process of displacement, and the oil was mainly displaced by mobility adjustment of surfactant-polymer slug before the breakthrough.

**3.2. Migration of Chemical Agents.** The change of chemical concentration is of great significance for surfactant-polymer flooding to enhance oil recovery; the smaller the loss, the farther the working distance, the higher the efficiency of enhanced oil recovery. After the surfactant-polymer slug was injected into the porous media, with the shearing of the reservoir, the complicated physicochemical change occurred, which lead to the adsorption and retention loss of chemical agents in the reservoir and adsorption loss in the oil layer, and thus resulted in differential migration of the chemical agents.

Figure 4 shows that, in the process of displacement, the relative concentration of HPAM has the same variation trend as that of KPS, but the loss of relative concentration of HPAM is much smaller than that of the surfactant. The time for HPAM to reach the maximum relative concentration from the occurrence at each sampling point is shorter than that of KPS, showing that, in the porous media, the migration loss of the polymer is smaller than that of the surfactant. With the complicated reaction of chemical solution, reservoir fluids, and reservoirs, the precipitation, adsorption, and retention in reservoirs and partitioning in oil may lead to the loss of surfactant.

At the follow-up water flooding process, the concentration of the polymer decreases rapidly, while the concentration of the surfactant decreases slowly, showing that the retention loss of KPS in pores is more significant than that of HPAM during surfactant-polymer flooding, whereas, in the follow-up water flooding process, some adsorbed and retained surfactants began to flow. In porous media, as the migration distance increases, the difference between the relative concentration of polymer and surfactant is larger and larger, and the chromatographic separation of polymer and surfactant is indicated by dimensionless breakthrough time and dimensionless isoconcentration distance, as shown in Table 3.

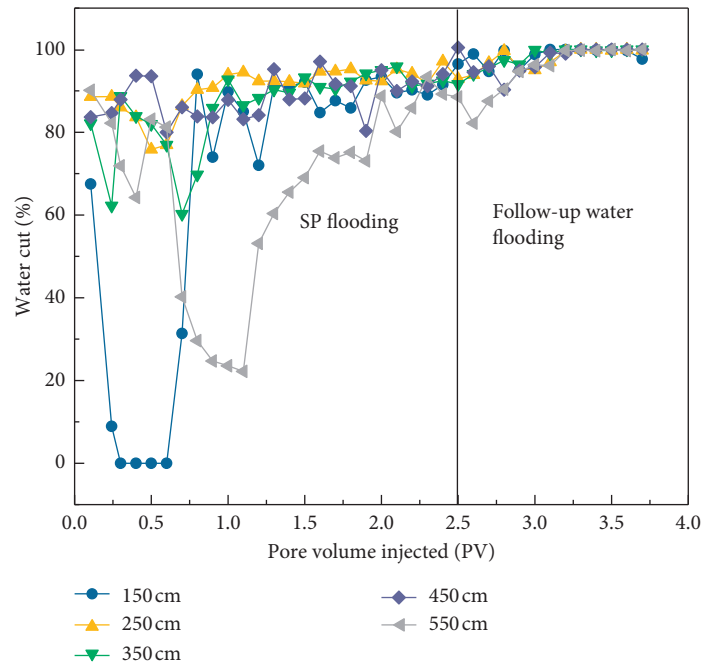


FIGURE 3: Variation of water cut with pore volume at sampling points.

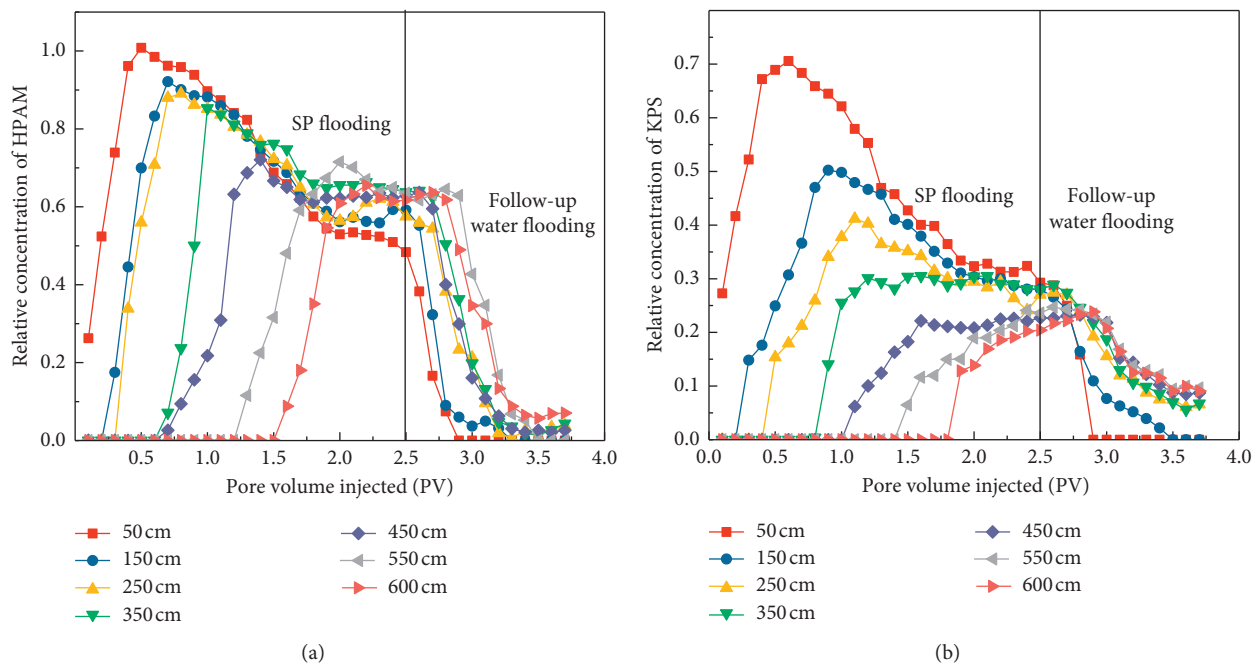


FIGURE 4: Variation of the relative concentration of polymer and surfactant at each sampling point: (a) relative concentration of HPAM; (b) relative concentration of KPS.

Table 3 shows the chromatographic separation parameters of polymer and surfactant at different positions. The dimensionless breakthrough time of HPAM increased from 0.1 to 1.092, while that of KPS increased from 0.1 to 1.308. With the increase in migration distance, the dimensionless breakthrough time of surfactant was gradually longer than that of polymer, and the longer the migration distance, the more serious the chromatographic separation. Besides, surfactant loss was significantly higher than polymer loss in

porous media. The dimensionless concentration distance of polymer and surfactant increased from 0 at 50 cm to 0.65 at 600 cm. Thus, the working distance of KPS is shorter than that of HPAM.

**3.3. Emulsification of Surfactant-Polymer Flooding.** During the core experiment, emulsification successively occurred from near and far from the injection inlet. Emulsification firstly

TABLE 3: Dimensionless breakthrough time and isoconcentration distance of chemical agents (sampling loss volume is deducted).

Sampling distance (cm)	Dimensionless breakthrough time		Dimensionless isoconcentration distance (Wp-s)
	Polymer	Surfactant	
50	0.1	0.1	0
150	0.190	0.190	0.09
250	0.274	0.368	0.18
350	0.436	0.609	0.19
450	0.652	0.816	0.40
550	0.922	1.078	0.62
600	1.092	1.308	0.65

occurred at 50 cm from the inlet and then moved forward with the injection of the surfactant-polymer slug. The emulsification at each point occurred at the pore volume of 0.2, 0.3, 0.5, 0.9, 1.4, 1.7, and 1.9 PV, respectively, as shown in Figure 5, which was related to the change of KPS concentration.

The emulsification images show that emulsification firstly occurs at 50 cm; then, with the injection of surfactant-polymer slug, emulsification occurs at each point successively; the color of emulsion gradually changes from yellowish brown to dark brown and finally to yellowish brown; afterward, the color gradually becomes lighter, and the emulsification gradually disappears at the end of follow-up water flooding. The concentration of chemicals at the emulsion time was measured, as shown in Table 4, and the concentration of KPS at each sampling point changes steadily, while that of HPAM is in weak regularity. In the surfactant-polymer flooding process, the emulsifier is a primary factor of the formation of emulsification; only when the emulsifier concentration reaches a particular value, can stable emulsification be formed. The emulsion formed at each point is mostly oil-in-water emulsions, and the water-in-oil emulsion is formed at 150 cm with a low water cut.

The micrograms of emulsion show that when emulsification occurs at a sampling point, the particle size of emulsion changes in a broad range, and the stability of the emulsion is reduced. With the continuous injection of the surfactant-polymer system, the concentration of chemical agents continuously increases, the stability of the emulsion is improved, and the particle size starts to become medium and small (Figure 6).

In the process of experiment, emulsion variation is divided into three stages: "generation, emulsification, and disappearance," and the emulsification at a sampling point is divided into three stages: initial, intermediate, and final emulsification. At the initial stage, when emulsifier concentration meets the condition of emulsification, emulsification starts, but it is irregular and uneven, the emulsion size distributes widely, and the emulsion stability is poor. During the intermediate stage, the emulsifier concentration becomes relatively stable, and the emulsion size is relatively regular, generally 0–12  $\mu\text{m}$ . Intermediate emulsification included medium and stable emulsification; with medium emulsification, 3–6  $\mu\text{m}$  droplets decrease, while 6–9  $\mu\text{m}$  droplets increase; with stable emulsification, 0–6  $\mu\text{m}$  droplets predominate, while 6–12  $\mu\text{m}$  droplets reduce. The final stage of emulsification is a stage with

high water cut; as the water cut increases, the chemical agent concentration decreases, the necessary conditions for maintaining emulsification gradually disappear, the emulsification degree is weak, and the size of the emulsion droplet is narrower, in a range of 0–6  $\mu\text{m}$ . Table 5 lists the variation of emulsification at each point.

From 50 cm to 600 cm, the emulsifying period at each point gradually shortens, and the duration of the intermediate stage gradually shortens likewise. In the process of surfactant-polymer flooding, the surfactant-polymer slug continuously strips and emulsifies the residual oil, leading to the continuous change of oil droplet size in the emulsion. The emulsion and the residual oil interact to form a new emulsion, so the water cut fluctuates greatly. With the increase in migration distance, the concentration of surfactant decreases gradually, the stripping ability of the surfactant-polymer slug to residual oil decreases, leading to the decrease in amount of newly emulsified oil in emulsion, the emulsifying ability of the surfactant-polymer system decreases, and the duration of the intermediate stage of emulsification shortens accordingly. The longer the migration distance, the lower the effective concentration of surfactant. In this case, the surfactant is mainly lost due to the resisting absorption, retention, and distribution loss in porous media and maintaining the stability of the emulsion system, and the stripping ability of the emulsified system to residual oil is weak. When the migration distance increases to a particular value, the surfactant-polymer system cannot form a stable emulsion.

With the increase in migration distance, the emulsifying ability becomes weak, and the viscosity retained of the polymer is at a low level. In this process, the surfactant-polymer slug has a weak ability of mobility control. In the reservoir, the emulsion flows in the curve, which we can regard as the displacing phase. As Figure 7 shows, the analysis on variation of emulsion viscosity shows that, after emulsification occurs, the mobile phase in porous media is emulsion, and the variation of viscosity at each point is relatively uniform, indicating that, in the process of surfactant-polymer flooding, emulsification can play the role of adjusting mobility and enlarging the swept volume. With a stronger emulsifying system, the stripping effect of emulsification to residual oil is higher than that of weaker emulsification. However, with the increase in migration distance, the emulsification distance and the duration of the intermediate emulsification may decrease.



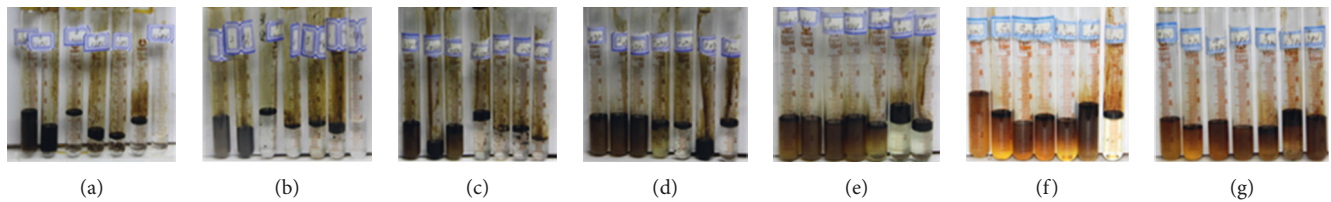


FIGURE 5: Sample image of emulsification at each point of surfactant-polymer flooding: (a) 0.2 PV; (b) 0.3 PV; (c) 0.5 PV; (d) 0.9 PV; (e) 1.4 PV; (f) 1.7 PV; (g) 1.9 PV.

TABLE 4: KPS concentration at each point at the time of emulsification.

Sampling point	50 (cm)	150 (cm)	250 (cm)	350 (cm)	450 (cm)	550 (cm)	600 (cm)
KPS concentration (mg/L)	462	444.6	461	422	490	389	388

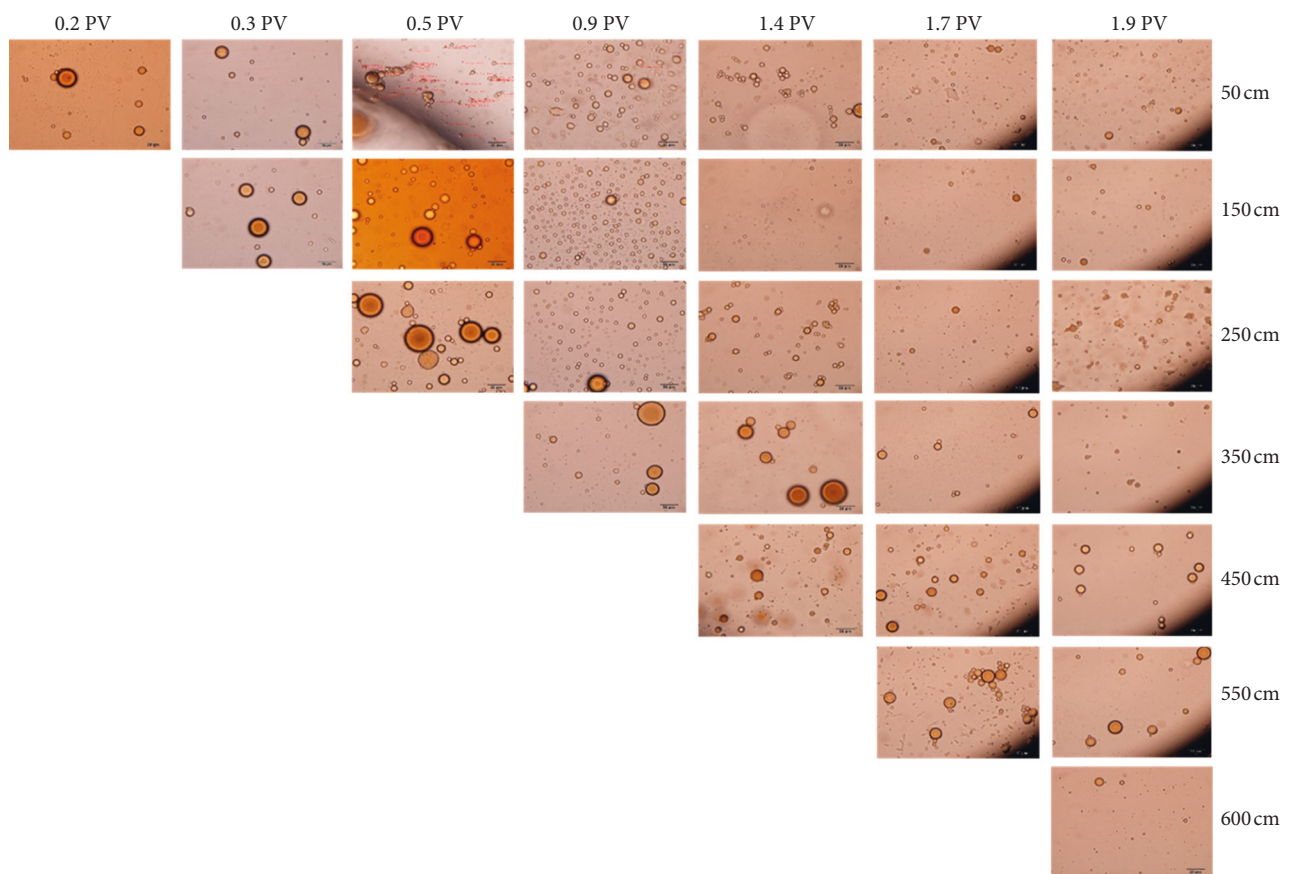


FIGURE 6: Microphotograph of emulsion (1,000 $\times$ ) at the sampling point. The pore volume is the injected volume of the injection inlet. The first picture of each sampling point means the occurrence of emulsification at the sampling point.

TABLE 5: Emulsification changes at each point.

Sampling point (cm)	Emulsifying period (PV)	Initial emulsification (PV)	Intermediate emulsification		Final emulsification (PV)
			Medium (PV)	Stable (PV)	
50	2.5	0.2–0.5	0.5–1.2	1.2–1.5	1.6–2.6
150	2.28	0.29–0.57	0.57–1.43	1.43–2.29	2.38–2.48
250	2.08	0.46–0.73	0.82–1.54	1.54–2.27	2.27–2.45
350	1.81	0.78–1.21	1.21–1.55	1.55–2.25	2.25–2.59
450	1.39	1.14–1.55	1.55–2.13	2.13–2.37	2.37–2.53
550	1.22	1.31–1.62	1.62–1.93	1.93–2.39	2.39–2.53
600	1	1.38–1.45	1.45–1.60	1.60–2.1	2.1–2.45

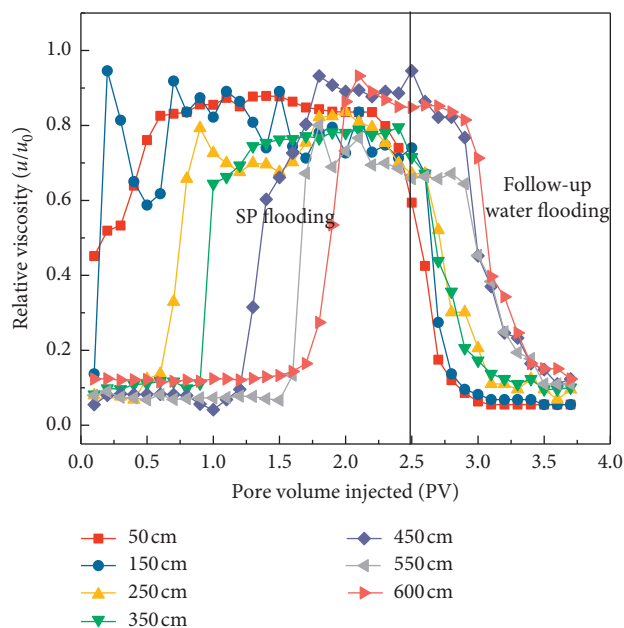


FIGURE 7: Variation of emulsion viscosity.  $u$  is the viscosity of emulsion.  $u_0$  is the viscosity of the surfactant-polymer solution and  $u_0 = 14$  mPa·s.

#### 4. Conclusions

With a long sand-packed core with multiple sample points, the surfactant-polymer flooding core experiment was carried out, and the surfactant-polymer slug increased oil recovery by 17.88%. During the surfactant-polymer flooding process, there is a chromatographic separation between polymer and surfactant, the dimensionless breakthrough time of polymer is 1.092 while that of surfactant is 1.308, and the dimensionless equal concentration distance of the chemical is 0.65.

The emulsification occurs when the concentration of KPS meets the requirement of emulsification, and emulsions began to appear at all sampling points and gradually moves forward with the migration of surfactant. As the migration distance increases, the duration of initial and intermediate stages gradually shortens, while the chemical agent concentration decreases, and the ability of the surfactant-polymer slug to emulsify and strip residual oil decreases gradually, and the surfactant concentration has a substantial effect on the emulsification strength and time.

With the increase in migration distance, the ability of mobility control of the surfactant-polymer slug becomes weak. The emulsification in the process of surfactant-polymer flooding can effectively increase the viscosity of the displacing phase, and the effect of emulsification on enhanced oil recovery is to control the mobility and enlarge the swept volume.

#### Notation

PV: Pore volume  
 HPAM: Hydrolyzed polyacrylamide  
 KPS: Petroleum sulfonate  
 HPLC: High-performance liquid chromatography  
 YP30001: The type of analytical balances

DV II-T: The type of viscometer  
 FY-31: The type of thermostat.

#### Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

#### Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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