Research Article

Synthesis and Properties of a Dendrimer Amphiphilic Polymer as Enhanced Oil Recovery Chemical

Xiaoping Qin,1,2 Sheng Zhu,1 Qionglin Shi,3 and Cuixia Li1

1School of Chemical Engineering, Sichuan University of Science and Engineering, Zigong 643000, China
2State Key Laboratory of Molecular Engineering of Polymers (Fudan University), Shanghai 200433, China
3Onshore Oilfield Operation Area, PetroChina Jidong Oilfield Company, Tangshan 063000, China

Correspondence should be addressed to Xiaoping Qin; 948801727@qq.com

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A dendrimer amphiphilic polymer (A-D-HPAM) was synthesized by aqueous solution polymerization of acrylic acid (AA), acrylamide (AM), 2-acrylamido-2-methyl-1-propane sulfonic acid (AMPS), hydrophobic monomer of cetyl dimethyl allyl ammonium chloride (DMCAAC-16), and skeleton monomer of GA1.0, using ammonium persulfate and sodium bisulfite as initiators. The chemical structure of A-D-HPAM was, respectively, analyzed by Fourier transform infrared spectrometer (FTIR), nuclear magnetic resonance (NMR) spectroscopy, and scanning electron microscope (SEM). The tackifying property, the resistance of shear, temperature and salt, the interfacial tension, and the oil displacement performance of A-D-HPAM were determined. Compared with solutions of HPAM (hydrolyzed polyacrylamide) and HPAM-SDBS (sodium dodecyl benzene sulfonate), A-D-PAM exhibits the optimal properties, especially achieving the enhanced oil recovery (EOR) of 15.1%.

1. Introduction

The synergistic effect of polymer-surfactant mixtures plays an important role in the enhanced oil recovery (EOR) [1–5]. Because the polymer can improve the viscosity of displacing fluid and increase the sweep efficiency, the surfactant can decrease the interfacial tension and enhance the oil washing efficiency of displacement media [6–8]. However, due to the poor shear resistance of the current polymer and the existence of chromatographic separation in porous media after compounding with surfactant, the oil displacement performance of polymer-surfactant binary flooding technology needs to be improved [9, 10].

To resolve the bottleneck problem of the development of polymer-surfactant binary flooding technology, functional monomers (such as 2-acrylamido-2-methyl-1-propane sulfonic acid and N-ethylpyrrolidone) were mostly introduced into the polymer molecular chain by domestic and foreign researchers to enhance the chain strength to improve the shear resistance of the polymer. Moreover, it was reported that polymers with dendritic, star-shaped, and hyperbranched structures had advantages in shear resistance [11, 12]. In terms of reducing chromatographic separation, surfactants with low adsorption loss and good compatibility with polymers were mainly used for replacing polymer-surfactant binary flooding technology [13–15]. However, the above-reported methods only focused on solving one of the low shear resistance and chromatographic separation problems in polymer-surfactant binary flooding system [16, 17].

Therefore, in this study, a dendrimer amphiphilic polymer (A-D-HPAM) was synthesized and used for replacing polymer-surfactant binary flooding technology. The branch chains, hydrophobic and hydrophilic groups, and three-dimensional network structure in A-D-HPAM were helpful to improve the chemico-physical properties of the tackifying property, the resistance of shear, temperature and salt, the interfacial tension, and the oil displacement performance of A-D-HPAM. Thus, the poor shear resistance of the reported hydrolyzed polyacrylamide (HPAM) can be effectively overcome [18–20]. Also, the dual characteristics of polymer and surfactant in A-D-HPAM were derived from...
introducing hydrophobic and hydrophilic groups, which can effectively solve the chromatographic separation issue in polymer-surfactant binary flooding technology [21, 22]. Meaningfully, the oil displacement experiment results demonstrated that EOR of A-D-HPAM (15.1%) was much higher than that of HPAM-SDBS (10.9%) and HPAM (8.6%).

2. Experimental

2.1. Instruments and Reagents. Reagents were all analytical pure reagents, without further purification before use, such as acrylamide (AM), acrylic acid (AA), sodium hydroxide, 2-acrylamide-2-methyl-1-propane sulfonic acid (AMPS), ethylenediamine, methyl acrylate, ethanol, acetone, sodium chloride, potassium chloride, magnesium chloride, sodium sulfate, calcium chloride, cetyl dimethyl allyl ammonium chloride (DMDAAC-16), sodium bisulfite (SDS), ammonium persulfate (APS), and sodium dodecyl benzene sulfonate (SDBS). All reagents were purchased from Chengdu Kelong Chemical Reagent Factory. The dendritic skeleton monomer (GA1.0) was prepared according to our previous report [23]. The composition of ions in the injected water is shown in Table 1.

The following instruments were used in this study. The electronic constant speed mixer (JHS-1, Hangzhou Instrument Motor Co., Ltd.), the digital rotational viscometer (NDJ-5S, Shanghai Fangrui Instrument Co., Ltd.), the DK constant temperature water bath (Tianjin Taiste Instrument Co., Ltd.), the XF-grinder (Guangdong Xinfei Fashion Co., Ltd.), the JSJ electric heating constant temperature blast drying oven (Chengdu Shengjie Technology Co., Ltd.), the nondiluted Ubbelohde viscometer (CN61M, Jiangsu Zhejing Glass Instrument Factory), the WGZ precision blast drying oven (Shanghai Keheing Industrial Development Co., Ltd.), the 2PB advection pump (Beijing Xingda Technology Development Co., Ltd.), the rotary evaporator (RE52CS-1, Shanghai Yarong Biochemical Instrument Factory), the scanning electron microscope (VEGA-3SBU, Beijing Dongxiyi Technology Co., Ltd.), the Fourier infrared spectrometer (FTIR-650, Tianjin Zhongke Ruijie Technology Co., Ltd.), the nuclear magnetic resonance instrument (Bruker-AC-E200, Bruker, Switzerland), the vacuum freeze dryer (Zhejiang Xiangsheng Purification Technology Co., Ltd.), and the interfacial tension meter (YS-ZL1020 Yingsa Instrument Technology Co., Ltd.).

2.2. Methods for Synthesizing A-D-HPAM. 30 g of deionized water and 6 g of AA were added into the three-necked flask, and the pH of the obtained solution (solution A) was adjusted to 7-8 using NaOH. The solution A was added with 6.1 g of AM, 0.5 g of AMPS, 0.86 g of DMCAAC-16 (70 wt.%), 0.08 g of GA1.0, and some of deionized water, respectively, to achieve a total monomer concentration of 25 wt.% (solution B). The temperature of solution B was maintained constantly at 40°C by the thermostatic water bath, and then the initiators (n_{APS}:n_{SDS} = 1:1) were added into the solution B. Finally, A-D-HPAM was obtained after 4 hours of polymerization. HPAM was prepared by the same process, but without adding DMCAAC-16 and GA1.0. The polymerization reaction of A-D-HPAM is shown as follows:

2.3. Structural Characterization of A-D-HPAM. The structures and functional groups of A-D-HPAM were characterized by FTIR-650, and ^1H nuclear magnetic resonance spectra of A-D-HPAM were obtained by Bruker-AC-E200 NMR. The microstructure of A-D-HPAM and HPAM was observed by VEGA-3SBU SEM.
2.4. Measurement of Viscosity-Average Molecular Weight. All experiments were conducted at 25°C. 1 M NaCl solution was used for the preparation of 500 mg/L of A-D-HPAM solution (solution C) and 500 mg/L of HPAM solution (solution D). 10 mL of 1 M NaCl was added into the Ubbelohde viscometer through the filling tube, and the air tube was sealed. The solution in the Ubbelohde viscometer was gently sucked into the timing tube until the solution reaching 5 mm above the upper timing mark. Then, loosening the timing tube allows the solution to freely flow down. The flowing time was recorded during the solution falling from the top edge of the upper timing mark-line to the top edge of the bottom timing mark-line. This method was also used to measure the flow time for solution C and D. The viscosity-average molecular weight (M) can be calculated from the following Mark–Houwink equation:

\[ \eta_r = \frac{t}{t_0} = \frac{\eta}{\eta_0}, \]

(1)

\[ \eta = KM^\alpha, \]

(2)

where \( \eta_r \) is the dimensionless relative viscosity, \( t \) is the flow time of 1 M NaCl solution with the unit of s, \( t_0 \) is the flow time of solution C or D with the unit of s, and \( \eta_0 \) and \( \eta \) are the intrinsic viscosities of 1 M NaCl solution and solution C or D with the unit of cm³/g. The dimensionless constants of \( K \) and \( \alpha \), respectively, used the value of 4.75 \times 10^{-3} and 0.8 obtained from the industrial polymers handbook [24] and \( M \) is the dimensionless viscosity-average molecular weight.

2.5. Methods for Performance-Evaluation of A-D-HPAM

2.5.1. Determination of Apparent Viscosity. The apparent viscosity of the following solutions was measured by NDJ-5S digital rotational viscometer under the rotating speed of 30 r/min at 60°C. (1) Solutions of A-D-HPAM with a certain concentration of 500 mg/L, 1000 mg/L, 1500 mg/L, 2000 mg/L, and 2500 mg/L were prepared with the injected water. The measured apparent viscosity of A-D-HPAM solutions was used for evaluating the tackifying properties. (2) To understand the shear resistance, the abovementioned A-D-HPAM solutions were sheared for 30 s at 20000 r/min using the XF-grinder. After elimination of the bubbles in the solutions by standing, the apparent viscosity was measured at the same experimental condition. (3) 2000 mg/L of A-D-HPAM solution was distributed into different wide mouth bottles. These bottles were sealed and placed at different temperatures for 24 h, then measuring the apparent viscosity for testing the temperature resistance. (4) Solutions of NaCl, CaCl₂, and MgCl₂ with different mass concentrations were prepared with deionized water, which were used for preparing 2000 mg/L of the A-D-HPAM solution and then measuring the apparent viscosity for determination of salt resistance.

2.5.2. Determination of Resistance Coefficient and Residual Resistance Coefficient. A one-dimensional sand filling pipe experiment was used to study the flow resistance of polymer solution. The experiment was carried out at 60°C. The
internal diameter and the length of the one-dimensional sand filling pipe were 2.5 cm and 25 cm, respectively. The inside was filled with 80–120 mesh quartz sand. The experimental steps were shown as follows: (1) the quartz sand filled in the one-dimensional sand filling mold was completely saturated with water, namely, the injected water was filled into the one-dimensional sand filling mold at an injection rate of 10 mL/min; meanwhile, the injection pressure was recorded after stabilization. (2) The polymer solution with a mass concentration of 2000 mg/L was injected into the one-dimensional sand filling mold at an injection rate of 10 mL/min and the injection pressure was recorded after stabilization. (3) For subsequent water drive, the injection water was injected into the one-dimensional sand filling mold again at an injection rate of 10 mL/min. The injection pressure was recorded after stabilization. The resistance coefficient and the residual resistance coefficient were calculated by the following formula:

\[
RF = \frac{P_p}{P_{w1}},
\]

\[
RRF = \frac{P_w}{P_{w2}},
\]

where \( RF \) is the dimensionless resistance factor, \( RRF \) is the dimensionless residual resistance factor, and \( P_{w1} \), \( P_p \), and \( P_{w2} \) are the steady pressures in the 1\(^{st} \), 2\(^{nd} \), and 3\(^{rd} \) step with the unit of MPa, respectively.

### 2.5.3. Measurement of Interfacial Tension

2000 mg/L of A-D-HPAM solution was prepared with injection water. After giving the parameters of the interfacial tensiometer, the high-density solution (A-D-HPAM solution) was added into the measuring cup to the marking line, raising the cup and adjusting the platinum ring immersed in the high-density solution about 5 mm. Then, the low-density solution (crude oil with the viscosity of 26.6 mPa\( \cdot s \) at 60°C) was re-added into the density solution according to instruction of the YSZL1020 interfacial tensiometer, waiting for the obvious stratification and measuring the interfacial tension.

### 2.5.4. Determination of Oil Displacement Performance

The one-dimensional sand filling pipe experiment was also used to estimate the ability of A-D-HPAM solution for improving oil recovery. The experiment was carried out at 60°C. A-D-HPAM solution was prepared by the injected water. The apparent viscosity of the crude oil was 26.6 mPa\( \cdot s \) at 60°C. The inner diameter and the length of the one-dimensional sand filling pipe were 2.5 cm and 30 cm, respectively. The one-dimensional sand filling pipe was filled with 80–120 mesh quartz sand with the permeability of 0.304 \( \mu \)m\( ^2 \) and the porosity of 35.1%. The steps of oil displacement experiment were shown as follows: (1) the injected water was injected into the one-dimensional sand filling pipe at the rate of 2 mL/min in the stable injection speed. (2) The crude oil was injected into the one-dimensional sand filling pipe at the rate of 1 mL/min until only crude oil following out. Then, the valves at both ends of the one-dimensional sand filling pipe model were closed for crude oil aging at 60°C for 24 h. (3) The injected water was injected into the one-dimensional sand filling pipe model at the rate of 2 mL/min until the water concentration reaches 95% in the displacement fluid. (4) 2000 mg/L of A-D-HPAM with 0.4 pore volume (PV) was injected into the one-dimensional sand filling pipe at the rate of 2 mL/min. (5) The injected water was re-injected into the one-dimensional sand filling pipe at the rate of 2 mL/min until the water concentration reaches 95% in the displacement fluid. The oil recovery rate was calculated by the following equation:

\[
E_A = E_T - E_W,
\]

where \( E_A \) is the enhanced oil recovery rate by the flooding of A-D-HPAM solution, \( E_T \) is the oil recovery rate of the whole displacement process, and \( E_W \) is the oil recovery rate of water flooding.

### 3. Results and Discussion

#### 3.1. Structure Characterization of A-D-HPAM

##### 3.1.1. FT-IR Spectra of A-D-HPAM

The FT-IR spectra of A-D-HPAM are shown in Figure 1. The absorption peak at 3425 cm\(^{-1} \) was attributed to the stretching vibration of N-H in -CONH\(_2\) in the branched chain of A-D-HPAM. The peak at 2922 cm\(^{-1} \) was due to the antisymmetric stretching vibration of C-H. The absorption peak at 2854 cm\(^{-1} \) corresponded to the symmetric stretching vibration of methylene. The peak at 1650 cm\(^{-1} \) was caused by the stretching vibration of C=O in -CONH in the branch skeleton. The characteristic absorption peak at 1565 cm\(^{-1} \) was related to the in-plane bending of N-H in -CONH\(_2\) in the branch chain. The characteristic absorption peak at 1451 cm\(^{-1} \) represented the in-plane bending of C-H. The peak at 1408 cm\(^{-1} \) was due to the stretching vibration of C-N in -CONH\(_2\). The peak at 1184 cm\(^{-1} \) was related to the in-plane shacking of primary amide (-NH\(_2\)) in the branch chain. The peak at 1121 cm\(^{-1} \) was caused by the stretching vibration of tertiary amine (C-N) in the branch skeleton. The peak at 1045 cm\(^{-1} \) was due to the O stretching vibration of sulfonic group (-SO\(_3\)) in the AMPS chain segment around the branch chain. The peak at 624 cm\(^{-1} \) was assigned to the in-plane shacking of primary amide (-NH\(_2\)). The FT-IR spectra indicate that A-D-HPAM has been successfully synthesized.

##### 3.1.2. \(^1\)H-NMR Spectrum of A-D-HPAM

The \(^1\)H-NMR spectrum of A-D-HPAM is shown in Figure 2. The \(^1\)H-NMR spectrum shows that the chemical shifts at 0.79 ppm (peak a) and 1.19 ppm (peak b) for \(^1\)H protons in -CH\(_3\) and -CH\(_2\)- of \(-\text{CH}_3\text{CH}_{12}\text{CH}_3\) in the hydrophobic monomer chain. The chemical shift at 1.44 ppm (peak c) was due to \(^1\)H protons in -\(\text{CH}_3\text{CH}_{12}\text{CH}_3\) in the branch chain and -CH\(_3\) in AMPS. The chemical shift at 2.05 ppm (peak d) was assigned to \(^1\)H protons of -\(\text{CH}_3\text{CH}_{12}\text{CONH}_2\) and -\(\text{CH}_3\text{CH}_{12}\text{COONa}\) in the branch chain. The chemical shift at 2.29 ppm (peak e) was due to \(^1\)H protons of -\(\text{CH}_3\text{CH}_{12}\text{CONH}_2\) and -\(\text{CH}_3\text{CH}_{12}\text{COONa}\).
in the branch chain and \(-\text{NH-CO-CH}_2\) in the branch skeleton. The chemical shift at 2.42 ppm (peak f) was assigned to \(^1\)H protons of \(-\text{NH-CO-CH}_2\) in the dendritic skeleton. The chemical shift at 2.71 ppm (peak g) was due to \(^1\)H protons of \(-\text{N-CH}_2-\text{CH}_2-\text{N}\) and \(-\text{CO-CH}_2-\text{CH}_2-\text{N}\) in the dendritic skeleton. The chemical shift at 2.97 ppm (peak h) was assigned to \(^1\)H protons of \(-\text{N-CO-CH}_2\) in the hydrophobic monomer chain and \(-\text{NH-CO-CH}_2\) in the dendritic skeleton. The chemical shift at 3.65 ppm (peak i) was assigned to \(^1\)H protons of \(-\text{CH}_2-\text{SO}_3\text{Na}\) in AMPS, and \(-\text{N-CH}_2-\text{CH}_2-\text{N}\) in the hydrophobic monomer chain. The chemical shift at 5.89 ppm (peak j) was assigned to \(^1\)H protons of \(-\text{CO-NH}\) in the dendritic skeleton and \(-\text{CO-NH}\) proton in the branch chain. The \(^1\)H-NMR spectrum further confirmed the successful synthesis and structure of A-D-HPAM.

3.2.3. SEM Observation of A-D-HPAM. Comparative SEM observations of HPAM and A-D-HPAM are shown in Figure 3. Figures 3(a) and 3(b) show the micromorphology of HPAM magnified 2000 times and 1000 times, respectively. Meanwhile, Figures 3(c) and 3(d) show the micromorphology of the A-D-HPAM magnified 2000 times and 1000 times, respectively. Comparative SEM observations (Figures 3(a) vs. 3(c) and 3(b) vs. 3(d)) showed that the structure of HPAM was relatively loose with many holes, relatively large gaps between chains, and low entanglement degree of molecular chains for HPAM. While the three-dimensional network structure was observed in SEM observations (Figures 3(c) and 3(d)) of A-D-HPAM with cross chains and high degree of entanglement of molecular chains for A-D-HPAM. Comparative SEM observations of HPAM and A-D-HPAM were conducive to understanding the improved morphological and chemico-physical properties of A-D-HPAM.
3.1.4. Viscosity-Average Molecular Weight. As shown in Table 2, the viscosity-average molecular weights of HPAM and A-D-HPAM are 329,607.2 and 382,612.0, respectively.

3.2. Evaluation of Chemicophysical Properties for A-D-HPAM

3.2.1. Comparative Tackifying Properties of HPAM and A-D-HPAM Solutions. As shown in Figure 4, the apparent viscosity of HPAM and A-D-HPAM solutions increased with the increase of concentration at the same experimental conditions. It was not obvious for the enhancement of the apparent viscosity of A-D-HPAM in the experiments of low mass concentration (<1500 mg/L). Significantly, it can be found that the great increase of the apparent viscosity of A-D-HPAM in the experiments that the concentration exceeded 1500 mg/L. Especially, for 2500 mg/L of A-D-HPAM solution, its apparent viscosity reached even up to 765.2 mPa·s, which was 26 times higher than that of HPAM solution at the same mass concentration. The significant increase of the apparent viscosity of A-D-HPAM was caused by the introduced hydrophobic group in the molecular chain of A-D-HPAM. Namely, increasing the concentration of the polymer solution until reaching a critical association concentration, the easy association between the main chains of A-D-HPAM made the significant enhancement of apparent viscosity.

3.2.2. Comparative Shear Resistance of HPAM and A-D-HPAM Solutions. As shown in Figures 5 and 6, the shear resistance of A-D-HPAM was excellent. The viscosity retention rate of A-D-HPAM reached 90% while it was about 65% for that of HPAM, which may be due to multiple branch chains of A-D-HPAM. At the same shear rate, there were few impacts on the molecular weight of the A-D-HPAM by the breakage of some branch chains. Therefore, the loss of viscosity was relatively small, resulting in high viscosity retention rate of A-D-HPAM. In addition, A-D-HPAM had the three-dimensional network structure and the high degree of entanglement between molecular chains (still entanglement with each other after shearing), which was conducive to viscosity recovery for obtaining its high viscosity retention.

3.2.3. Comparative Temperature Resistance of HPAM and A-D-HPAM Solutions. In Figure 7, it can be found that the apparent viscosity of HPAM and A-D-HPAM solutions decreased with the increase of temperature and the temperature resistance of A-D-HPAM solution was stronger than that of HPAM. Obviously, there was a slight change for the apparent viscosity of HPAM and A-D-HPAM solutions when the experimental temperature was below 35°C. For experimental temperature was higher than 35°C, it can be seen the sharp decrease of apparent viscosity of A-D-HPAM solution. Especially, after saving HPAM and A-D-HPAM solutions at 65°C for 24 h, the viscosity retention of the A-D-HPAM was 50% while that of HPAM was only 40%, which reconformed that the temperature resistance of A-D-HPAM solution was stronger than that of HPAM.
3.2.4. Comparative Salt Tolerance of HPAM and A-D-HPAM Solutions. The comparative salt tolerance of HPAM and A-D-HPAM solutions is shown in Figures 8–10. Clearly, it can be found that salt tolerance of HPAM and A-D-HPAM solutions to divalent ions (Ca$^{2+}$ and Mg$^{2+}$) was worse than that to monovalent ions (Na$^{+}$). Due to the fact that the

<table>
<thead>
<tr>
<th>Solutions</th>
<th>Flow time (s)</th>
<th>ηr</th>
<th>[η] (cm$^3$/g)</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mol/L of NaCl solution</td>
<td>76.4</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>500 mg/L of HPAM solution</td>
<td>110.6</td>
<td>1.447</td>
<td>778.2</td>
<td>3296072.5</td>
</tr>
<tr>
<td>500 mg/L of A-D-HPAM solution</td>
<td>112.8</td>
<td>1.512</td>
<td>876.8</td>
<td>3826120.7</td>
</tr>
</tbody>
</table>

Figure 4: Comparative tackifying properties of HPAM and A-D-HPAM solutions.

Figure 5: Comparative shear resistance of HPAM and A-D-HPAM solutions.
higher valence of metal ions and the greater degree of potential reduction, the divalent metal ions had much stronger effects than the monovalent metal ions on the apparent viscosity of HPAM and A-D-HPAM solutions. In addition, when the concentration of NaCl ($C_{NaCl}$) was 2000 mg/L–4000 mg/L, or $C_{CaCl_2}$ and $C_{MgCl_2}$ were 300 mg/L–600 mg/L, there was an obvious peak for the apparent viscosity of A-D-HPAM solution, which may be resulted from hydrophobic association effect of A-D-HPAM solution and metal ions shield effect to the interaction between positive and negative ions in A-D-HPAM solution. On the one hand, hydrophobic association effect of A-D-HPAM increased with the increase of salinity for the constant concentration of A-D-HPAM. On the other hand, metal ions shield effect was feasible to inhibit the interaction between positive and negative ions in A-D-HPAM macromolecules, leading to the stretched molecular chains and the increased apparent viscosity. However, when $C_{NaCl}$ was higher than 6000 mg/L, or $C_{CaCl_2}$ and $C_{MgCl_2}$ were higher than 900 mg/L, the apparent viscosity of A-D-HPAM solution decreased significantly, which may be caused by intramolecular curling of A-D-HPAM molecular chain due to the increase of salinity and the decrease of charge repulsion effect on the molecular chain.
3.2.5. Comparative Resistance Factor and Residual Resistance Factor of HPAM and A-D-HPAM Solutions. The variation of pressure with the increase of injection volume during the experiment is shown in Figure 11 and Table 3.

Obviously, it can be obtained that the resistance factor (RF) and the residual resistance factor (RRF) of HPAM and A-D-HPAM were 12.2 and 2.0 and 25.5 and 5.0, respectively. At the same experimental conditions, RF and RRF of A-D-HPAM were 12.3 and 3.0 higher than those of HPAM, respectively. The greater the RF, the greater the seepage resistance in the pore medium, leading to the high swept volume in the polymer flooding stage. The higher the RRF, the greater the decrease of the permeability in the pore medium, which was conducive to improving the swept volume in the subsequent water driving stage. Therefore, A-D-HPAM had significant advantages in improving the swept volume.

3.2.6. Comparative Interfacial Tension. The interfacial tension between 1000 mg/L HPAM, HPAM-SDBS, A-D-HPAM, and crude oil was shown in Table 4 at the experimental temperature of 30°C.

It could be found that both HPAM-SDBS and A-D-HPAM had the ability to lower down the interfacial tension. At 30°C and 1000 mg/L, compared with HPAM, the interfacial tension of HPAM-SDBS and A-D-HPAM decreased by 1.66 mN/m and 2.11 mN/m, respectively, which indicated that A-D-HPAM had strong ability to reduce interfacial tension.

3.2.7. Comparative Oil Displacement Performance. The variation of oil recovery with the cumulative injection volume for 2000 mg/L of HPAM, HPAM-SDBS, and A-D-HPAM solutions is shown in Figure 12. It could be obtained that 2000 mg/L of HPAM, HPAM-SDBS, and A-D-HPAM could improve oil recovery by 9.6%, 10.9%, and 15.1%, respectively. A-D-HPAM had the strongest EOR capacity, followed by polymer-surfactant binary flooding (HPAM-SDBS), and HPAM was the worst EOR capacity. Addition of polymer was helpful to improve sweep efficiency, and addition of surfactant was conducive to improve oil washing efficiency. Due to the possible chromatographic separation phenomenon, the synergistic effect of polymer and surfactant on improving sweep efficiency and oil washing efficiency was lowered down. Thus, the enhanced oil recovery capacity of HPAM-SDBS was slightly higher than that of HPAM. The good viscosity, shear resistance, and
hydrophobic association of A-D-HPAM were helpful to improve sweep efficiency. Also, the amphiphilic properties of A-D-HPAM can reduce the interfacial tension and eliminate the chromatographic separation. Therefore, the ability of A-D-HPAM in enhancing oil recovery was better than that of HPAM and HPAM-SDBS.

4. Conclusion

A-D-HPAM was prepared by aqueous solution polymerization using AM, AA, AMPS, DMCAAC-16, and GA1.0. For $C_{A-D-HPAM} > 1500 \text{ mg/L}$, tackifying properties of A-D-HPAM were good. For $C_{A-D-HPAM} = 2000 \text{ mg/L}$, the apparent viscosity of A-D-HPAM was 20 times that of HPAM. At the same shear speed, the viscosity retention rate for 2000 mg/L of A-D-HPAM was 25% higher than that of HPAM. A-D-HPAM in 2000 mg/L–4000 mg/L of NaCl solution or in 300 mg/L–600 mg/L of CaCl₂ and MgCl₂ solution had a good tackifying capacity. RF and RRF of A-D-HPAM and HPAM were 25.5 and 5.0 and 12.2 and 2.0, which indicated that A-D-HPAM exhibited a good ability to establish flow resistance. Compared with HPAM and HPAM-SDBS, A-D-HPAM had better shear resistance and stronger capacity for lowering the interfacial tension. The oil displacement experiment results demonstrated that EOR of A-D-HPAM (15.1%) was much higher than that of HPAM-SDBS (10.9%) and HPAM (8.6%).

Data Availability

All basic data supporting the research results are available in the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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