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The mechanism for pore-throat scale emulsion displacing residual oil after water flooding

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A R T I C L E I N F O

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A B S T R A C T

The reservoir characteristics and fluid property of Daqing Oilfield was taken as the research platform. The emulsion was prepared by core displacement experiment. The stability of emulsion was analyzed by measuring the Zeta potential at different emulsifier concentrations. The emulsion viscoelasticity was also measured in different water cut stage. Displacement experiments of emulsion and surfactant flooding (poor emulsification) at the same interfacial tension were conducted, and the displacement efficiency of pore-throat scale emulsion (particle size greater than throat diameter but less than pore diameter) was studied. Using a visual sand packed model, displacement experiments allowed for the observation of the pore-throat scale emulsion displacing oil drop and columnar residual oil, and the deformation and migration process of residual oil were analyzed. The mechanism of pore-throat scale emulsion displacing residual oil was studied. The results show that with the emulsifier concentration increases, the absolute value of emulsion Zeta potential increases, and the stability of emulsion increases, the stability of pore-throat emulsion is preferably. When the water cut is 63.2%, the emulsion viscoelasticity is most favorably. When the emulsifier concentration is 0.4%, the emulsion flooding can enhance recovery efficiency by 9.84% compared to surfactant flooding with the same interfacial tension. The viscoelastic deformation of the pore-throat scale emulsion can pull the oil drop and columnar residual oil, and the residual oil can migrate.

1. Introduction

Alkaline, surfactant and polymer (ASP) flooding has achieved useful results. Laboratory experiments and field tests show that its recovery efficiency increases by approximately 20% compared with water flooding (Cheng et al., 2002), and emulsification is beneficial to recovery efficiency. When more emulsion is observed in the produced fluid of oil wells, the water cut greatly decreases, and the development effect is better (Li et al., 2003). A large number of studies have been performed to examine the emulsion recovery efficiency. Liu et al. (2014) studied the influence of surfactant emulsification on recovery efficiency at high temperature in a high salinity reservoir. The study showed that injecting a surfactant with favorable emulsifying properties can improve the recovery efficiency by approximately 4% compared to injecting a surfactant with poor emulsifying properties. Mandal et al. (2010, 2015) studied the emulsion displacement efficiency, and the results showed that oil-in-water emulsion behaves as a pseudoplastic fluid. The displacement mechanism mainly decreases the mobility and the oil-water interfacial tension. Guillen et al. (2012a, 2012b) suggested that water-in-oil emulsion can control mobility; the mechanism for improving displacement efficiency is mainly the increase in the capillary number. Lei et al. (2008) suggested that the mechanism for emulsification enhancing recovery efficiency is mainly emulsification kick-off, entrainment and mobility control. However, most studies have been conducted at atmospheric pressure, and mechanical stirring has been responsible for emulsion formation (Al-Wahaibi et al., 2015; Demikhova et al., 2014; Qiu. 2013; Guillen et al., 2012a, 2012b; Abdul and Farouqali. 2003), and the formation mechanism, particle size, stability and rheological properties of emulsion are quite different from the emulsion forming in the reservoir, the latter is more complicated. Currently, studies on emulsion flooding mostly focus on improving the swept volume (Vellaiyan and Amirthagadeswaran, 2016; Kar et al., 2016; Zhou et al., 2016; Son et al., 2014), less on examining the micro-displacement mechanism, and the particle size in the emulsion is usually not addressed (Karambeigi et al., 2015; Engelke et al., 2013; Kumar et al., 2010; Cortis and Ghezzehei. 2007). Emulsions with different particle sizes can play different roles in

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displacing residual oil; however, no studies have been conducted to examine these properties. Therefore, the reservoir characteristics and fluid property of Daqing Oilfield was taken as the research platform, and pore-throat scale emulsion was chosen as the subject, the emulsion was prepared at the outlet of the core by displacement experiment. The stability and viscoelasticity of emulsion was measured. The displacement efficiency of emulsion was studied compared with the surfactant flooding (poor emulsifying properties), and the mechanism for pore-throat scale emulsion displacing residual oil was analyzed through visual displacement experiment.

2. Experiments

2.1. Experimental materials

2.1.1. Surfactant

The emulsifier is a mixture of betaine type surfactant and polyoxyethylene ether nonionic surfactant. The surfactant is petroleum sulfonate (SLPS) in surfactant flooding; it has poor emulsifying properties.

2.1.2. Oil

The oil is prepared from wellhead crude oil from Daqing Oilfield and aviation kerosene, and the viscosity is 9.5 mPa·s at 45 °C.

2.1.3. Brines

The aqueous-phase salinity affects the interfacial tension and the water solubilization capacity (Bera et al., 2014, 2014), and it also the stability of emulsion. Low ionic strength brine favors the formation of stable emulsion (Wang and Alvarado. 2012). When the aqueous-phase salinity is too high, it has unfavorable effect on the stability of emulsion (Moradi et al., 2011). The salinity of formation water is very low in Daqing Oilfield, so the effect of salinity on emulsion stability was not discussed. Two kinds of brine were used to simulate the salinity of Daqing Oilfield. One is simulated as formation water of Daqing Oilfield with the total salinity of 6578.0 mg/L, and it is used to saturate cores. The Na^+ is 2073.4 mg/L, Ca^{2+} is 52.5 mg/L, Mg^{2+} is 11.9 mg/L, CO_3^{2-} is 344.3 mg/L, HCO_3^- is 2801.2 mg/L, Cl^- is 1279.0 mg/L, and SO_4^{2-} is 15.8 mg/L. The other is the injection water of Daqing Oilfield with the total salinity of 729.3 mg/L, and it is used to displace oil. The Na^+ is 231.2 mg/L, Ca^{2+} is 34.1 mg/L, Mg^{2+} is 24.3 mg/L, CO_3^{2-} is 90.0 mg/L, HCO_3^- is 225.1 mg/L, Cl^- is 88.7 mg/L, and SO_4^{2-} is 36.0 mg/L.

2.1.4. Cores

Three kinds of cores was used in the experiments. The first is the artificial core, its size is 4.5 cm × 4.5 cm × 30 cm, and the permeability is approximately $1000 \times 10^{-3}\ \mu m^2$. It is used to prepare emulsion. The second is the artificial core, its size is 4.5 cm × 4.5 cm × 60 cm, and it is used in the displacement experiments. The third is the visual core, it is constructed from a transparent acrylic plate and 50-mesh sand.

2.1.5. Instruments

A TX500D spinning drop interfacial tensiometer, a Brookhaven Zeta potentiometric measurement, an HW-4A double thermostat, an ISCO pump, an MCR302 rheometer, a Welch1402 vacuum pump, a BK-DM320/500 digital biological microscope with a magnification of 40-1600 × .

2.2. Experimental methods

The experiments were done at 45 °C.

2.2.1. Preparation of emulsion

The emulsion process in reservoir was simulated by core displacement experiment. The experimental procedure was as follows: The core was saturated into the formation water, and oil was injected into the core to displace the formation water to obtain the status of origin oil saturation. After 6 h, the injection water was injected to displace the oil at a rate of 0.3 mL/min until the water cut was 98%. Then, 1 PV (pore volume) emulsifier solution was injected into the core at the same rate, and the emulsion was collected at the outlet of the core.

2.2.2. Measurement of zeta potential

After the emulsion was prepared, the 10 mL emulsion was collected and was added to the vessel of Zeta potential measurement, and the Zeta potential was measured (Duzyol and Ozkan. 2014).

2.2.3. Measurement of emulsion viscoelasticity

10 mL of the emulsion was used to measure the viscosity of emulsion, storage and loss modulus by the rheometer, and the average of three measurements was obtained.

2.2.4. Measurement of permeability after injecting emulsion

Water was injected into the core (its size is 4.5 cm × 4.5 cm × 30 cm) at a rate of 0.3 mL/min, and the pressure was recorded every 2 min, then the permeability was determined. 1 PV emulsion was injected into the core at a rate of 0.3 mL/min, and the pressure was also recorded. The water was injected into the core at the same rate until the pressure was stabilized. Finally the permeability was calculated after injecting emulsion.

2.2.5. Measurement of interfacial tension

The interfacial tension was measured by TX500D spinning drop interfacial tensiometer. The experimental procedure was as follows: The emulsifier solution was injected into a capillary by a injector, and gently tap the capillary wall to get rid of the bubbles in the tube. 0.5 μL oil was injected into the capillary with a micro syringe, and the capillary was put in the measuring cell, then the rotation control button was opened at the speed of 5000r/min, and the interfacial tension was recorded.

2.2.6. Displacement experiments

The experimental procedure of displacement experiments is similar to the preparation of emulsion. After water flooding to 98% of water cut, the chemical solution was injected at a rate of 0.3 mL/min into the core until the water cut is 98%, and the recovery percentage was calculated.

2.2.7. Visual core displacement experiments

The experimental method was the same as that the displacement experiments, and the injection rate of water and emulsifier solution was 0.01 mL/min.

3. Results and discussion

In my previous work (Zhou et al., 2017), the particle size distribution of formed emulsion were measured at different emulsifier concentrations and injection rates, and the emulsifier concentrations and injection rates for forming pore-throat scale emulsion were given. The results show that the emulsifier concentration is between 0.4% and 0.5%, and the injection rate is between 0.3 mL/min and 0.4 mL/min, the pore-throat scale emulsion can be formed. So particle size distribution of emulsion was not discussed.

3.1. Stability of pore-throat scale emulsion

The emulsion was prepared when the emulsifier concentration is 0.1%, 0.2%, 0.3%, 0.4% and 0.5% respectively, and the Zeta potential was measured, the experiment results are shown in Fig. 1.

The results show that the emulsion surface bears negative charge. With the emulsifier concentration increases, the absolute value of emulsion Zeta potential increases, and the stability of emulsion increases. When the emulsifier concentration is less than 0.3%, the absolute value of emulsion Zeta potential is small, and the stability of emulsion is poor. When the emulsifier concentration is 0.4%, the pore-throat scale