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ORIGINAL PAPER - EXPLORATION ENGINEERING

Experimental research on novel oil displacement and profile control system for heterogeneous reservoir

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Abstract
Polymer flooding and surfactant/polymer flooding (SP flooding) were mainly focused on the improvement in oil–water flow ratio and the reduction in oil–water interfacial tension. Preformed particle gel (PPG) flooding was mainly focused on the reservoir heterogeneity improvement. Each of these technologies has its own limitations. Heterogeneous system flooding (HS–PP flooding) was proposed as a novel flooding method aimed to improve oil–water flow ratio and reservoir heterogeneity at the same time. The HS–PP flooding system was composed of PPG and polymer solution. HS–PP flooding, polymer flooding and SP flooding as different chemical EOR methods were studied in laboratory in physical simulation heterogeneous model. Property of cubic expansion of PPG was researched by laser particle analyzer. The result shows that cubic expansion of PPG in simulation water is obvious and can be controlled. The effect of PPG on the diversion rate modification in double parallel sandstone model was obvious. The oil displacement experiments of the three different flooding systems with the same viscosity in physical simulation heterogeneous model were studied. The results show that the HS–PP flooding improves the oil recovery by 20.04%, comparing the result of 12.67% for polymer flooding and 16.66% for SP flooding, respectively. HS–PP flooding as a novel flooding method shows an excellent ability for stabilizing oil production and controlling water cut. The mechanism of the HS–PP flooding was discussed briefly. In addition to the viscoelastic displacement of polymers, the special circulation ability of "accumulating–deforming (collapsing)–accumulating again" of PPG is the main reason why the HS–PP flooding shows an excellent property for stabilizing oil production and controlling water cut.

Keywords Heterogeneous reservoir · Heterogeneous system flooding · Preformed particle gel · Profile control · Enhanced oil recovery

Introduction

As most of the major oil fields in China have entered high water cut stage, technology having the characteristics of stabilizing oil production and controlling water cut has become increasingly important (Willhite and Pancake 2008; He et al. 2009; Wei (2013); Hendraningrat and Zhang 2015; Li et al. 2015). Polymer flooding and polymer/surfactant flooding (SP flooding) are currently the most widely used chemical flooding technologies (Shah and Schechter 1977; Needham and Doe 1987). In principle, the two technologies increase the swept volume and improve the displacement efficiency mainly by increasing water phase viscosity and reducing the interfacial tension between oil and water phases (Prabir and Paşaoğlu 2004; Amaloei and Kharrat 2009; Yu et al. 2010). The applicability of the two widely used chemical flooding technologies in the heterogeneous reservoir is very poor. New technology for improving oil recovery in heterogeneous reservoir is of great significance. PPG flooding and synergistic system containing PPG featuring in excellent ability of stabilizing oil production and controlling water cut has attracted extensive interest recently (Cui 2011; Cao 2013; Zhang et al. 2014; Goudarzi et al. 2014; Chenet al. 2017; Zhao et al. 2018; Lenji et al. 2018; Liu et al. 2018). In this flooding system, PPG was mainly used for reservoir microstructure improvement. In this paper, HS–PP system composed of preformed particle gel and polymer solution was proposed as a novel flooding method aimed to improve oil–water flow ratio and reservoir heterogeneity at the same time. Property of cubic expansion and plugging property of PPG were researched in this paper. HS–PP flooding, polymer flooding and SP flooding as different

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chemical EOR methods were studied in laboratory in physical simulation heterogeneous model. The mechanism of the HS–PP flooding was discussed briefly. This paper is helpful for practical application of HS–PP flooding in oil field.

Experimental apparatus and materials

Experimental apparatus

The apparatus included viscometer (Brookfield DV-II), interfacial tension apparatus (TX-500C), laser particle analyzer (Mastersizer 3000), displacement equipment (pressure gauge, thermostat, physical simulation counter-rhythm model), PH meter, etc.

Experimental materials

The chemicals applied in the experiments, such as NaOH (≥ 99.5%), Na_2CO_3 (≥ 99.5%) NaCl (> 99.5%), $CaCl_2$ (> 96%) and $MgCl_2 \cdot 6H_2O$ (> 99%), were provided by Beijing Modern East Fine Chemical Co. The viscosity of the crude oil applied in the experiments was 17.46 mPa s at 57 °C. The ion composition of simulation water is shown in Table 1.

Polymer A with solid content of 90% and molecular weight of 15 million, surfactant B with solid content of 30% and PPG C with diameter of 300–600 µm and solid content of 86% were used for preparing the different flooding system. Double parallel sandstone model (Φ2.5 × 10 cm) with 2000 mD and 500 mD and physical simulation counterrhythm model (30 × 4.5 × 4.5 cm) combined of 3 vertical layers with 2000 mD, 800 mD and 100 mD were used for displacement experiment.

Experiments

Volume-expanding experiments of PPG

The measurement steps of particle size distribution of PPG before/after expanding by the laser particle analyzer are as follows:

1. Turn on the power supply according to the order of the laser particle analyzer, computer and printer, and fill the sample table with distilled water, turn on the pump and preheat the instrument for 10 min. Enter the operation procedure of the laser particle analyzer, establish the connection and then set the corresponding parameters.
2. After the series work of compensation measurement, optical path correction and blank measurement have been completed, according to the prompt of the software, the PPG sample with a certain dissolution time is added to the sample table as an appropriate concentration, and then the particle size analysis test is carried out.
3. Make parallel experiments, preserve the results and print the report according to the requirements.
4. Exit the procedure, turn off the power supply and fill the sample table with distilled water again to prevent residual particles from attaching to the lens.

Plugging properties of PPG

Take the double parallel sandstone model to study the plugging performance of PPG. According to the value of permeability, the two different permeability cores were marked as the low-permeability layer (LPL) and the high-permeability layer (HPL). The simulated water was injected at the rate of 0.4 mL/min. The diversion rate of different layers was calculated. When the diversion rate was stable, the PPG solution (400 mg/L) was injected for 0.8 Pv at the rate of 0.4 mL/min. And then the simulated water was re-injected at the rate of 0.4 mL/min. The diversion rates at different stages for each layer were calculated.

IFT measurement for SP system

The IFT between SP solution and crude oil was measured by spinning drop interfacial tensiometer TX-500C at 57 °C. A drop of oil was maintained horizontally by a microsyringe in a quartz cuvette tube which was full of SP solution (polymer 1500 mg/L; surfactant B 1000 mg/L). The tube was rotated at a high speed of 6000r/min under the action of the instrument. A charge-coupled device (CCD) camera captured the oil drop profile in the solution in real time and transferred data, and then the data were digitized and analyzed by software. IFT was directly calculated by employing the Laplace equation.

Viscosity measurement for different flooding systems

Measurement of viscosity was performed using a brinell viscometer DV-II. The polymer solution (polymer concentration 1500 mg/L), SP solution (polymer concentration 1500 mg/L; surfactant B concentration 1000 mg/L) and HP-PP solution (polymer concentration 1500 mg/L; PPG concentration 400 mg/L) viscosities were measured by brinell viscometer at 57 °C. Each sample was stirred at a speed of 250r/min for 5 min in a 57 °C water bath before measurement.

Table 1 Ion composition of the simulation water

Ions	$Na^+ + K^+$	Mg^{2+}	Ca^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	CO_3^{2-}	Total	pH at 25 °C
C (mg/L)	986.1	16.2	39.5	742.4	495.2	911.2	0	3190.6	8.2

Displacement experiment

Flooding effect for different flooding systems was evaluated by displacement experiment in physical simulation model.

The displacement procedure is as follows:

1. The model is saturated with simulation water in a vacuum state. So the pore volume is calculated by the water volume.
2. The model is flooded by the crude oil until no more water could be displaced. The oil saturation is calculated by the ratio of saturation oil volume to the saturation water volume in step 1.
3. The model is flooded by simulation water at a rate of 0.4 ml/min. When water cut reaches 98%, the model is flooded by one of flooding systems. When the injected flooding system volume reaches 0.5 PV, the model is flooded by simulation water again until no more oil could be displaced.

Results and discussion

Volume-expanding results of PPG

Expanding properties of PPG particles in the simulation water with the dissolution time were studied by the laser particle analyzer. PPG particle size and its cubic expanding results in simulation water with dissolution time at 57 °C are shown in Table 2.

The initial value of D_{50} is 442 µm. The value of D_{50} is 2.9 times of the initial value when the PPG is dissolved in the simulation water for 7 days. The value of D_{50} is 3.4 times of the initial value when the PPG is dissolved in the simulation water for 15 days. The result shows that the volume of PPG is expanded with the dissolution time and the expanding rate decreases after 7 days. The PPG particle size tends to be stable after 15 days. As the conclusion of Liu et al. (2018) about the expansion property of B-PPG, the cubic expansion of PPG in simulation water is obvious and finite. It satisfies the requirements of the heterogeneous system displacement. Expansion and insolubility of PPG in solution are the prerequisite for profile controlling.

Table 2 PPG particle size and its cubic expanding results at 57 °C

Sample	Dissolution time (days)	D_{10} (µm)	D_{50} (µm)	D_{90} (µm)
PPG	0	274	442	690
	1	374	1430	2560
	5	409	1290	2480
	7	430	1150	2370
	10	467	1490	2610
	15	482	1512	2635
	30	480	1510	2632

Plugging results of PPG solution

The plugging results of PPG solution in the double parallel sandstone model are shown in Fig. 1.

It can be seen from Fig. 1 that the effect of PPG on the diversion rate modification was obvious. After injecting 0.6Pv simulation water, the distribution rate of low-permeability layer and high-permeability layer was 8% and 92%, respectively. The diversion rate of high-permeability layer decreased rapidly after the injection of PPG solution. After injecting 0.5Pv follow-up simulation water, the distribution rate of low-permeability layer and high-permeability layer was 54% and 46%, respectively. The distribution rate of the high-permeability layer and the low-permeability layer has been effectively adjusted.

Displacement experiment of the three different flooding systems

The IFT between SP system and oil, the viscosities of different flooding system and the displacement experiment results are shown in Table 3.

All sorts of conditions including model porosity, oil saturation and viscosity of flooding system were very close. HS–PP flooding, SP flooding and polymer flooding show different effects from the view of the improved recovery. Based on the same recovery of water flooding (about 29%), oil recovery enhanced by HS–PP flooding was 20.04% compared with 12.67% by polymer flooding and 16.66% by SP flooding, respectively. HS–PP flooding shows better oil displacement effect than polymer flooding and SP flooding.

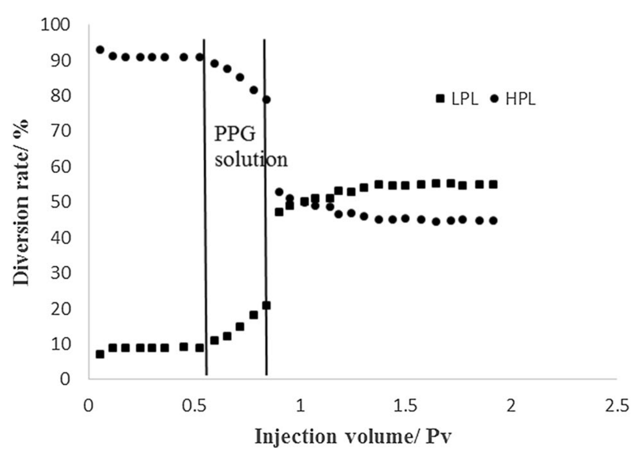

Fig. 1 The result of plugging properties of PPG in the double parallel sandstone model

Table 3 Properties of the different flooding systems and displacement experiment results

Flooding system	Model porosity (%)	S_{io} /%	c/μ/σ	Oil recovery by water (%)	EOR (%)	Ultimate recovery (%)
Polymer flooding	25.72	71.61	Polymer (1500)/11.6/–	28.65	12.67	41.32
SP flooding	26.77	73.76	Polymer/surfactant (1500/1000)/11.1/0.012	30.08	16.66	46.74
HP-PP flooding	26.36	71.68	Polymer/PPG (1250/400)/11.7/—	29.06	20.04	49.1

Remarks: S_{io}—initial oil saturation; EOR—enhanced oil recovery; c—concentration of flooding system, mg/L; μ—viscosity of flooding system, mPa s; σ—interfacial tension between flooding system and oil, mN/m

Mechanism of HS–PP flooding

Heterogeneous system is composed of polymer solution and PPG particles. It is a solid–liquid coexistence system. As a continuous phase, polymer solution not only play the role in conventional polymer flooding, but also carry the PPG particles as a dispersed phase into the reservoir. In the actual displacement progress, expanded PPG particles were injected into the model with the flooding system. The large pore path formed in the water flooding progress would be the preferred path of injected HS–PP flooding system. The expanded PPG particles resided in the macroscopic throats forming "accumulation" and blocked the large pore path making the subsequent displacement HS–PP system change the flow direction. The "accumulation" deformed or collapsed under a higher drive force, and they formed "accumulation" again when the force was small in the larger pore throats or channels. The special circulation ability of "accumulating–deforming (collapsing)–accumulating again" promotes their deep migration improving the heterogeneity of the physical model. Zhao et al. (2018) studied the restarting pressure gradient for preformed particle gel passing through pore-throat. Their research provided a way to evaluate the process of "plugging–deformation–restarting" for PPG passing through the pore-throat. They validated our hypothesis about the mechanism of PPG from microcosmic experiment. It is the reason why the HS–PP flooding shows an excellent ability for stabilizing oil production and controlling water cut.

Figure 2 shows the pressure change with injected volume of different flooding systems. In the subsequent water flooding stage, pressure drop rate for HS–PP flooding is the slowest. It also illustrates that the PPG particles can continuously deform and migrate in the model and have long-lasting profile adjustment ability.

Figure 3 shows the water cut change with injected volume of different flooding systems.

The water cut was greatly reduced by HS–PP flooding. Experimental phenomena and displacement mechanism are corresponding to each other. Relative to the water cut of water flooding, the maximum decrease in water cut after flooding HS–PP is 32%. The result is similar to the result of Lenji et al. (2018). Their results show that PPG was able to reduce water production by 30–65%.

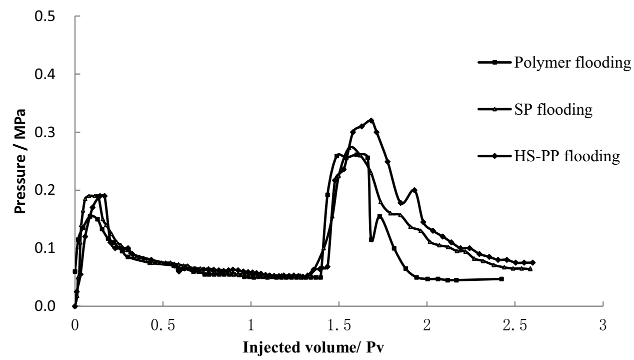

Fig. 2 Pressure change in displacement experiment in model

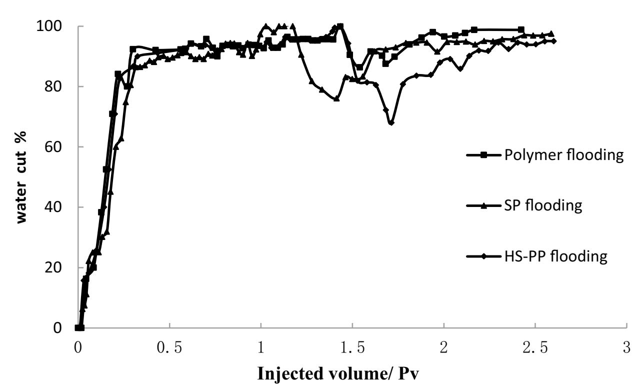

Fig. 3 Water cut in displacement experiment in model

Conclusion

1. The volume of PPG is expanded with the dissolution time, and the expanding rate decreases after 7 days. The PPG particle size tends to be stable after 15 days.
2. HS–PP flooding, SP flooding and polymer flooding show different effects from the view of the improved recovery. Based on the same recovery of water flooding, oil recovery enhanced by HS–PP flooding was larger than the ones by polymer flooding and SP flooding.
3. In addition to the viscoelastic displacement of polymers, the special circulation ability of "accumulating–deforming (collapsing)–accumulating again" of PPG promotes their deep migration improving the heterogeneity of the physical model. It is the main reason why the HS–PP flooding shows an excellent property for stabilizing oil production and controlling water cut.

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