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Experimental study and field application of surfactant-polymer flooding in offshore oilfield

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Restricted by the short life of the oil development platform and its high investment, offshore oilfield needs higher oil recovery rate in the early developmental stage so as to recover its investment fast. Therefore, polymer flooding method carried out in medium water cut period was proposed. The production performance improved through the use of polymer flooding in Bohai H oilfield, but became worse when the polymer flooding reached the end stage. The oil recovery increased by 10.5%. It is important to find a way to improve production performance other than polymer flooding. Therefore, this article optimizes surfactant-polymer flooding as the subsequent technology that enhances oil recovery. By using laboratory experiment to compare different experimental schemes, two important parameters including number of injection pore volume and injection timing were optimized. The research result was applied in field development of Bohai H oilfield. Based on the research results, this article concludes innovatively that surfactant-polymer flooding can enhance oil recovery significantly in offshore oilfield, and the number of injection pore volume and injection timing can affect the surfactant-polymer flooding obviously. It is reasonable when the number of injection pore volume is 0.3 PV for Bohai H oilfield; oil recovery can further increase if surfactant-polymer flooding is carried out in higher water cut period. The field application from 2013 to 2018 shows that the oil production performance of Bohai H oilfield can be improved significantly by using surfactant-polymer flooding; the daily oil production increased by about 1.25 times for average single well; and the oil recovery increment forecasted is 4.6% points. The research result can be used as an important reference for similar offshore oilfields to enhance oil recovery.

Key words: Surfactant-polymer flooding, enhancement of oil recovery, injection pore volume number, injection timing, offshore oilfield.

INTRODUCTION

Tapping the potential of the remaining oil is an important research work for the development of offshore oilfield, the geological conditions are usually complex and very heterogeneous, and this is a common phenomenon in offshore oilfields. Due to great distance between the injection and production well and the irregular well pattern of the offshore oilfield, the proven methods for enhancing oil recovery in onshore oilfield cannot be used in offshore oilfield directly. Restricted by this platform, work schedule arrangement and difficult construction, the

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Abbreviations: S/P, Surfactant-polymer; **PV,** pore volume.

development investment in offshore oilfield is higher than that of onshore oilfield, so it is important to realize high and stable production within the economy period.

From the aforementioned, in order to reduce the cost of offshore oilfield development, it is better to take the development method of water flooding or natural water energy. And with the progress of technology and needs of technicians (Salehi et al., 2013; Falode and Ojumoola, 2015; Aifen et al., 2011; Dongdong et al., 2016; Hongying et al., 2012), polymer flooding has become an important method for enhancing oil recovery, but this method will get worse if the scheme reaches the end of the stage. So it is necessary to search for subsequent methods that enhance oil recovery besides polymer flooding.

As the first oilfield that used S/P flooding for pilot test besides polymer flooding in Bohai bay, there are fewer researches that take references from scheme design and implementation process for Bohai H oilfield. Past research works mainly focused on the feasibility of S/P flooding by using laboratory experiment of one-dimensional core displacement, numerical simulation of mechanism model or small scale field test separately (Hongyan and Brian, 2013; Dandan, 2016; Miao et al., 2017; Yanli et al., 2012; Litao et al., 2015). There are fewer reports on the comprehensive use of the whole process including laboratory experiment, numerical simulation and field application for S/P flooding. In order to reduce the one-sidedness of research results, this article provides new insight into S/P flooding in offshore oilfield by using the whole process analysis.

Past studies were mainly on the schematic optimization of S/P flooding after using water flooding. Polymer flooding has already been applied in Bohai H oilfield and the remaining oil distribution is now more complex. There are fewer researches on S/P flooding scheme optimization. So this article is necessary for Bohai H oilfield.

OIL FIELD GENERAL INFORMATION

Bohai H oilfield has typical lacustrine and delta front deposit. Its porosity is 27.0 to 33.2% and permeability is 480×10^{-3} to 2265×10^{-3} μm^2; the lateral distribution of reservoir is stable, but the heterogeneity is strong. The permeability contrast is about 3.5 to 4.5; the temperature with deep 1700 m at the middle of the reservoir is about 58°C. The difference between reservoir original pressure and saturation pressure is 1.8 to 3.2 MPa. The reservoir water belongs to the $NaHCO_3$ type. The salinity of the reservoir water is 3250 to 5180 mg/L and the viscosity of underground oil is 12 to 25.0 cp. In order to improve the development situation of water flooding, polymer flooding was used in 2007, but it became worse from 2012. Thus, S/P flooding scheme was studied by using laboratory experiment and numerical simulation. The scheme was conducted in 2013. The practical production proved that S/P flooding method can improve the production performance besides polymer flooding in Bohai H oilfield.

EXPERIMENT PREPARATION

Experiment material and condition

The experimental materials mainly include:

(a) Two artificial cores located in parallel to reflect the reservoir heterogeneity. The permeability contrast between high permeability core and low permeability core is 4. The data of each core are shown in Table 1.
(b) The experimental water is made according to the ion composition of the water source well in Bohai H oilfield; its total mineralization is 4620 mg/L and viscosity is 0.46 cp at 58°C.
(c) The simulated oil is made up of dehydrated crude oil of Bohai H oilfield and kerosene. Its viscosity is 17.5 cp at 58°C.
(d) The polymer is used in actual production in Bohai H oilfield and the polymer solution concentration is 1200 mg/L.
(e) The surfactant-polymer system consists of 0.24% surfactant solution and polymer solution of 1200 mg/L.
(f) The constant temperature of the experiment is 58°C.

Experiment devices and process

The experimental devices mainly include: thermostat box, core gripper, Teledyne Isco high pressure and high precision plunger pump, pressure sensor, six-way valve, hand pump, intermediate container and oil-water separator. The experimental process is as shown in Figure 1.

Experiment scheme

In order to optimize the scheme of S/P flooding, 6 sets of experiments were designed (Table 2).

Experiment procedures

(a) Net weight was weighed after drying the core and vacuum saturated the formation water; wet weight was used to determine the pore volume of the core and to calculate its porosity.
(b) In determining the permeability of water phase, the core with saturated oil was connected to the experimental process and air was evacuated in the line, exerting confining pressure of 1.5 MPa under a constant temperature of 58°C for 2 h or more.
(c) Water flooding of two cores was done separately to make bound water; oil flooding of more than 10 PV number was used to measure the volume of water driven out and to calculate the bound water saturation, 24 h after aging.
(d) Two cores are connected in parallel into the experiment process. Water flooding, polymer flooding and S/P flooding were done under the constant velocity of 0.5 mL/min; the displacement pressure was recorded. Cumulative oil production and cumulative water production at different times before water cut is 98%.

EXPERIMENTAL RESULTS AND ANALYSIS

Contrast of development methods

Three development methods including water flooding (Scheme 1), polymer flooding (Scheme 2) and S/P

Table 1. Physical Properties of Experimental Artificial Cores.

Group	Core number	Diameter (cm)	Length (cm)	Permeability (10^{-3} μm^2)	Porosity (%)
1	H1	2.49	7.64	2107.5	32.5
	L1	2.41	7.93	528.3	27.3
2	H2	2.46	7.85	2043.6	31.8
	L2	2.45	7.62	506.2	27.1
3	H3	2.50	7.13	2260.7	31.6
	L3	2.48	7.66	567.1	28.6
4	H4	2.49	7.46	2107.1	33.1
	L4	2.51	7.95	487.5	28.5
5	H5	2.47	7.78	2160.8	32.7
	L5	2.47	7.89	512.8	28.2
6	H6	2.46	7.52	2175.6	32.9
	L6	2.48	7.93	538.6	28.4

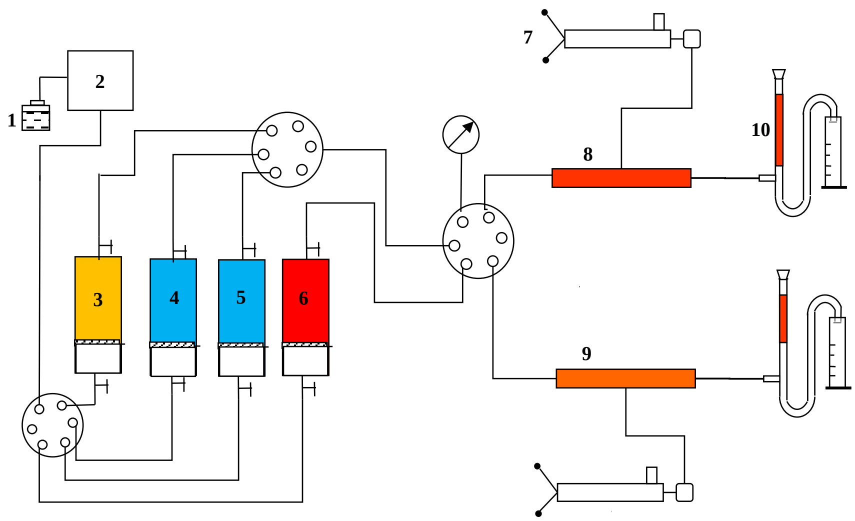

Figure 1. Devices and processes of experiment. 1-Working fluid; 2-constant-flux pump; 3-S/P system; 4-polymer; 5-injection water; 6-simulated oil; 7-hand pump; 8-high permeability core; 9-low permeability core; 10-oil-water separator.

flooding (Scheme 4) were contrasted in the experiment. The contrasting results are as shown in Figure 2a, b and c.

As shown in Figure 2a, compared to water flooding, the oil recovery increased by 10.2% with polymer flooding; and in contrast to pure polymer flooding, the oil recovery increased by 10.5% with S/P flooding. It can be seen that S/P flooding has notable effect than polymer flooding or water flooding. Figure 2b indicates the contrast of water cut under different development methods. It can be seen that the water cut funnel can be formed by polymer flooding, and the water cut dropped to 49.3% percentage. This is mainly due to the increment of resistance in high permeability core by polymer flooding; displacement medium is turned to low permeability core displacement; the problem of imbalance in vertical displacement of reservoirs has been weakened to some extent. In contrast to polymer flooding, the water cut funnel was formed again after carrying out S/P flooding; the water cut dropped to 16.5%. The water cut funnel width is wider

Table 2. Experimental schemes.

Scheme number	Core handling	Water flooding	Polymer flooding	S/P flooding	Subsequent polymer flooding
1	Saturated oil	Until water cut 98%	-	-	-
2	-	Until breakthrough of high permeability core	Until water cut 98%	-	-
3	-	-	Until water cut 85%	Injection S/P system solution 0.2 PV	Until water cut 98%
4	-	-	-	Injection S/P system solution 0.3 PV	
5	-	-	-	Injection S/P system solution 0.5 PV	
6	-	-	Until water cut 98%	injection S/P system solution 0.3 PV	

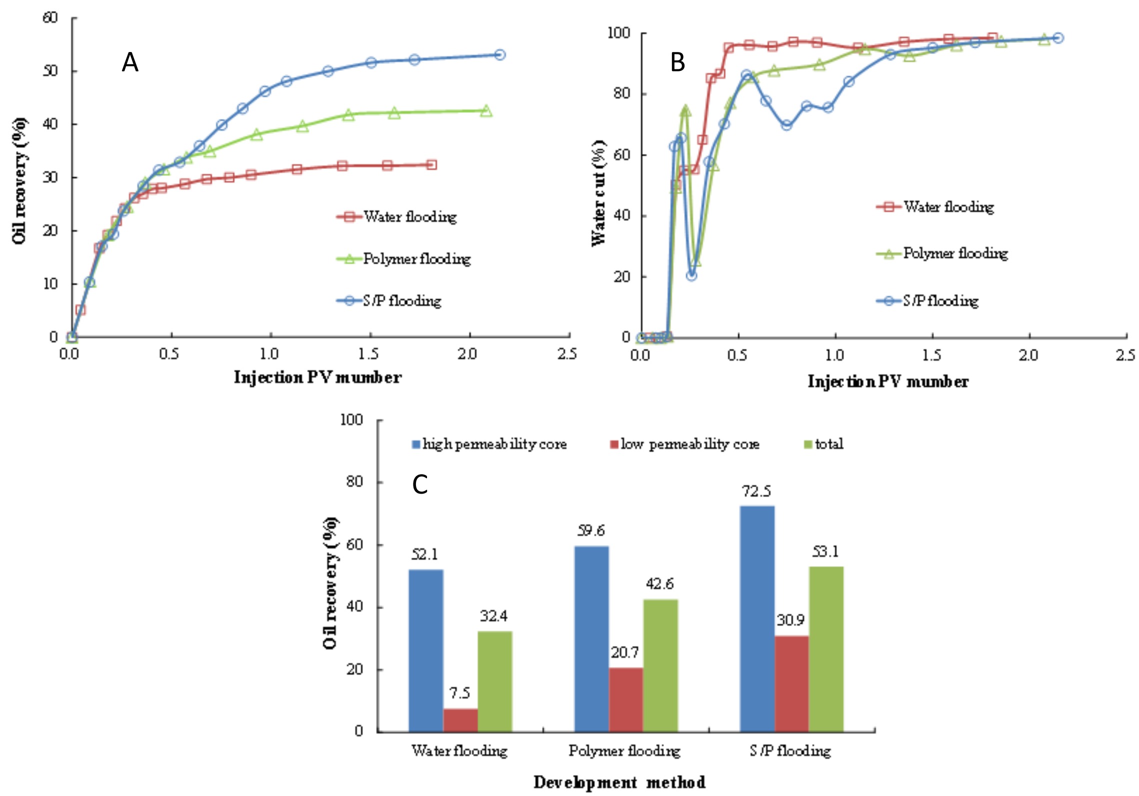

Figure 2. Contrast of different development method: (a) Relationship between oil recovery and injection PV number; (b) Relationship between water cut and injection PV number; (c) Oil recovery contrast of different development method.

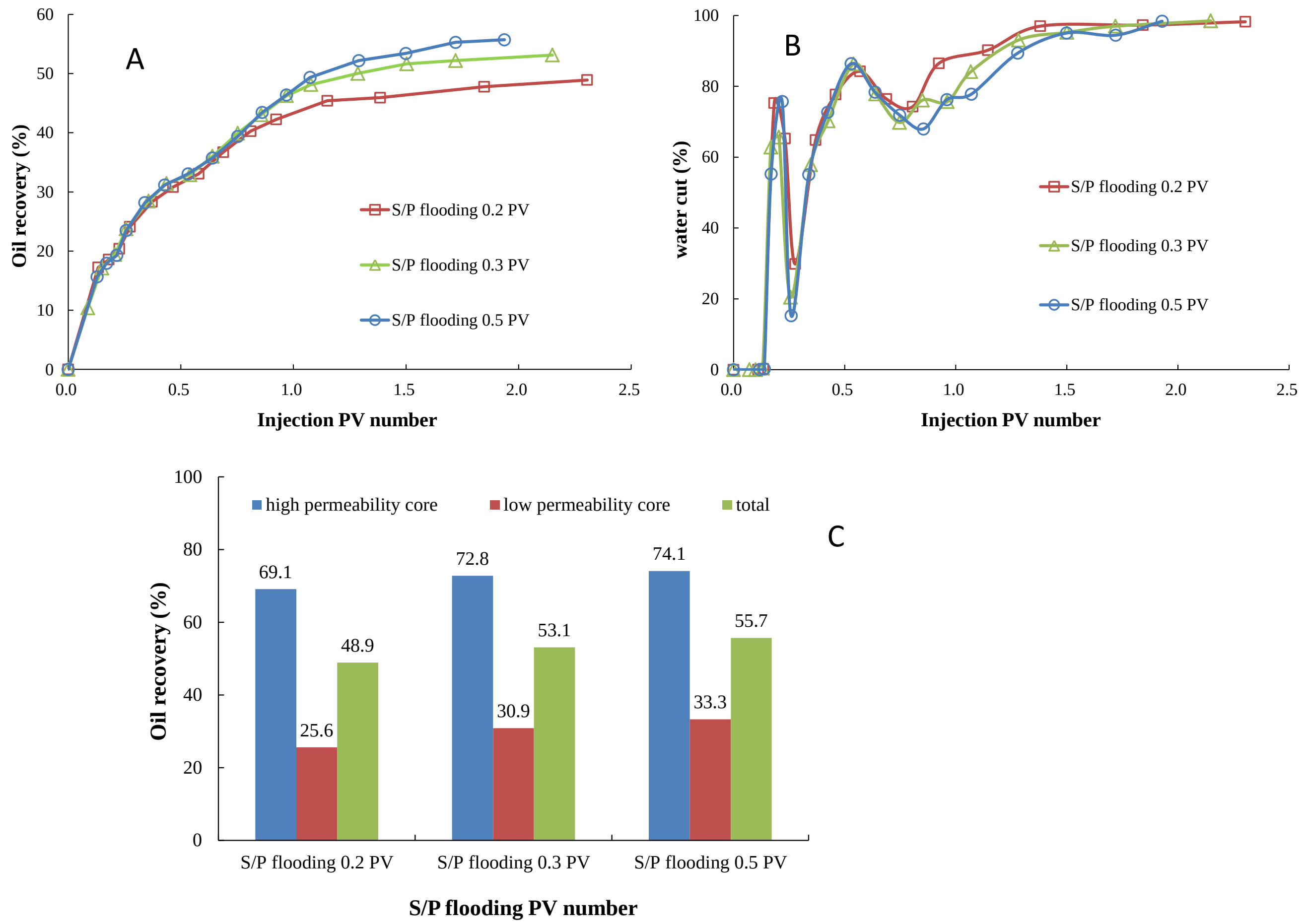

Figure 3. Contrast of different injection PV number: (a) Relationship between oil recovery and injection PV number; (b) Relationship between water cut and injection PV number; (c) Oil recovery contrast of different injection PV number.

than that of polymer flooding. It shows that the effective time is longer in S/P flooding. This is because S/P composite system can significantly reduce the interfacial tension of oil and water, so that the oil droplets can be easily deformed; the resistance decreases when the oil droplets pass through the pore channel. The highly dispersed residual oil in the hydrophilic rock is displaced, forming flowing oil. This leads to decreased water and increased oil. So it is more advantageous to choose the S/P flooding development method.

More detailed analysis is as shown in Figure 2c. Compared to water flooding, the capability of single polymer flooding to enhance recovery comes from the improvement of low permeability core production. The oil recovery increased by 13.2% in low permeability core and by 7.5% in high permeability core. This shows that polymer flooding can weaken the mobility difference between different permeability layers. S/P flooding can enhance microcosmic oil displacement efficiency to improve the total displacement effect. Compared to polymer flooding, the oil recovery increased by 10.2% in low permeability core, and by 12.9% in high permeability core.

Contrast of different injection PV numbers

In carrying out S/P flooding when water cut was 85%, the results of injection of 0.2 PV (Scheme 3), 0.3 PV (Scheme 4) and 0.5 PV (Scheme 5) were analyzed. The contrast results are as shown in Figure 3a, b and c.

As shown in Figure 3a, the oil recovery can be further improved with the increment of the PV number of S/P system. In contrast to the injection of 0.2 PV, the total oil recovery of the injection of 0.3 PV increased by 4.2%; whereas in contrast to the injection of 0.3 PV, the total oil recovery of the injection of 0.5 PV increased by 2.6%. Figure 3b shows the contrast of water cut under different injection PV numbers. It can be seen that the width of water cut funnel became wider with the increment of PV number. That means the effect time gets longer. But it should be noted that with the increment of injection PV

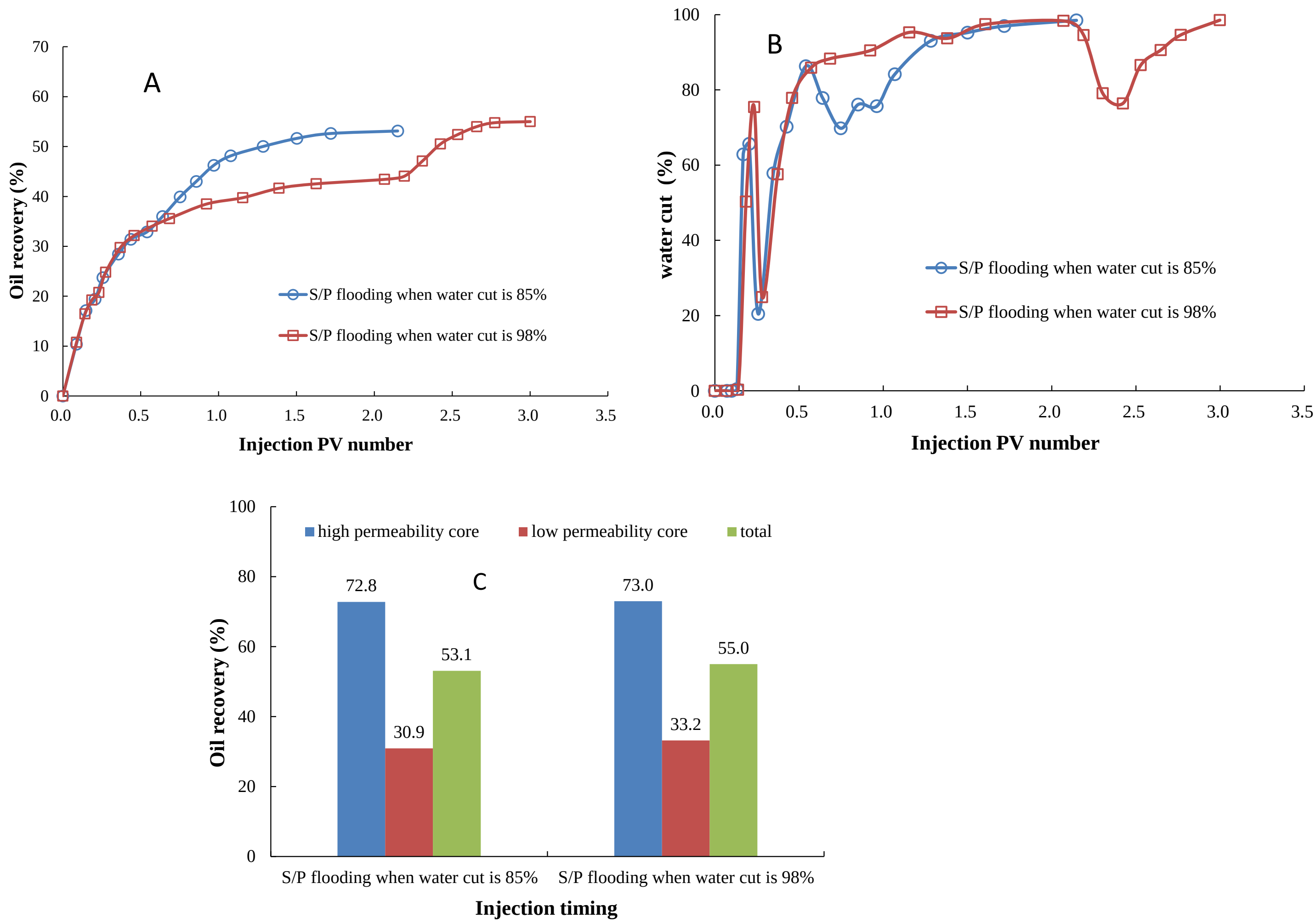

Figure 4. Contrast of different injection timing: (a) Relationship between oil recovery and injection PV number; (b) Relationship between water cut and injection PV number; (c) Oil recovery contrast of different injection timing.

number, the extent of recovery increase rate gradually decreases, if the price of surfactant is expensive (Liang et al., 2010). It is recommended that 0.3 PV is reasonable for S/P flooding.

As shown in Figure 3c, the extent of recovery increment of low permeability core is higher than that of high permeability core with the increment of injection PV number. It shows that oil recovery is enhanced mainly from low permeability layer.

Contrast of different injection timing

From the S/P flooding at 0.3 PV, the results of S/P flooding carried out when water cut was 85% (Scheme 4) and 98% (Scheme 6) were analyzed. The comparison results are as shown in Figure 4a, b and c.

In comparing the time when S/P flooding was done at water cut of 85%, oil recovery rate increased by 1.9% at water cut of 98%. Figure 4b shows the water cut funnel's width of two timings to be the same. The water cut decreased by 16.5% when S/P flooding was carried out at water cut of 85%; whereas the water cut decreased by 21.9% when S/P flooding was carried out at water cut of 98%. It shows that the extent of oil recovery will increase with increase in injection timing of water cut. Figure 4c shows that the oil recovery increment mainly comes from low permeability core; the oil recovery increased by 2.3% in low permeability core and increased by 0.2% in high permeability core.

With increase in the injection timing of water cut, the oil recovery can further increase. It indicates S/P flooding can improve the development situation effectively in high water cut period; considering the impact of the short lifetime of the platform and its high investment (Xianhon, 2011), if S/P flooding is done in higher water cut stage, it should prolong the lifetime of the platform and save the investment into consideration.

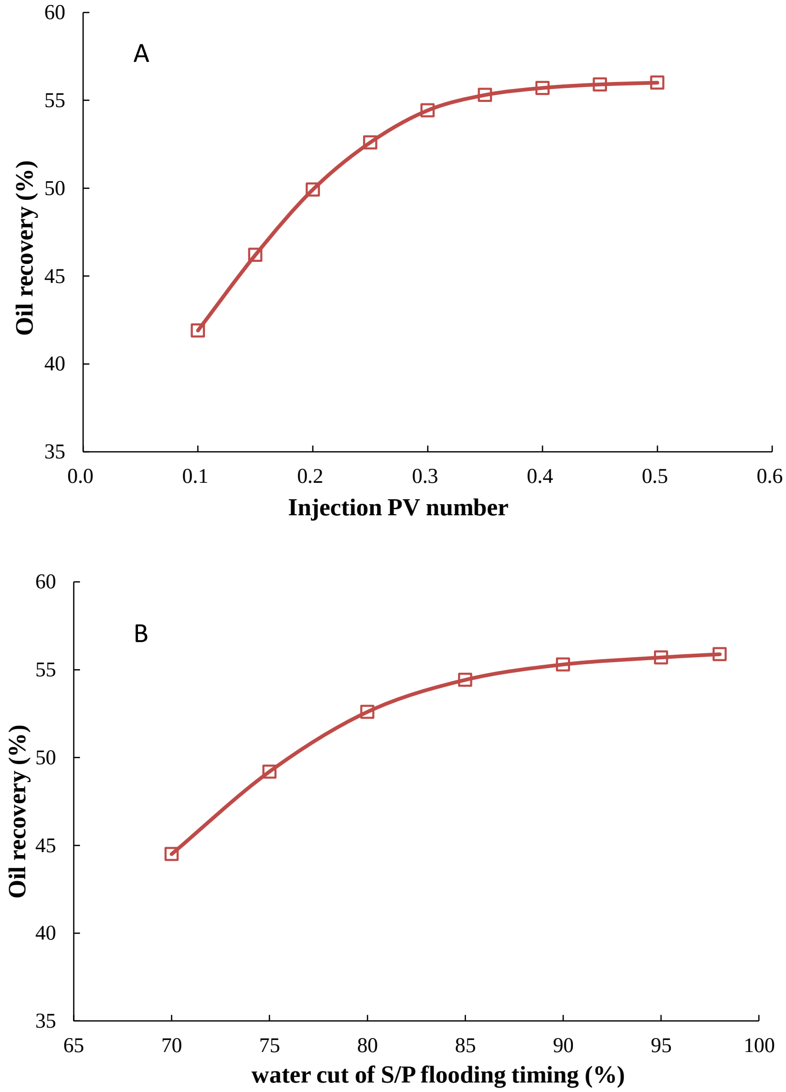

Figure 5. Contrast of parameter optimizes schemes: (a) Relationship between oil recovery and injection PV number; (b) Relationship between oil recovery and the water cut of injection timing.

VERIFICATION BY NUMERICAL SIMULATION METHOD

In order to verify the reliability of the experiment results, the article uses the numerical simulation method to optimize the injection PV number and the injection timing of S/P flooding. The simulator used is ECLIPSE numerical simulation software developed by Schlumberger Company. Combing polymer flooding module and surfactant module can lead to proper functioning of S/P flooding, such as: increase the viscosity of displacement phase, decrease the permeability of channeling-path, decrease the interfacial tension between water and oil, increase capillary number, etc.

The optimization of numerical simulation parameters mainly include two groups of schemes: the first group scheme was done under S/P flooding when the water cut was 85%. The scheme includes injecting S/P system solution of 0.1 PV, 0.15 PV, 0.2 PV, 0.25 PV, 0.3 PV, 0.35 PV, 0.4 PV, 0.45 PV and 0.5 PV separately. Figure 5a shows the contrast between the different schemes. The oil recovery increased when the injection PV number increased; when the PV number was less than 0.3 PV, the velocity of oil recovery curve increased fast. However, when the PV number is higher than 0.3 PV, the velocity of recovery curve increase became slow. It shows the degree of recovery increase became smaller. This is mainly because most residual oil had been displaced when the PV number reached 0.3 PV; the rest of the residual oil became harder to be displaced, so the

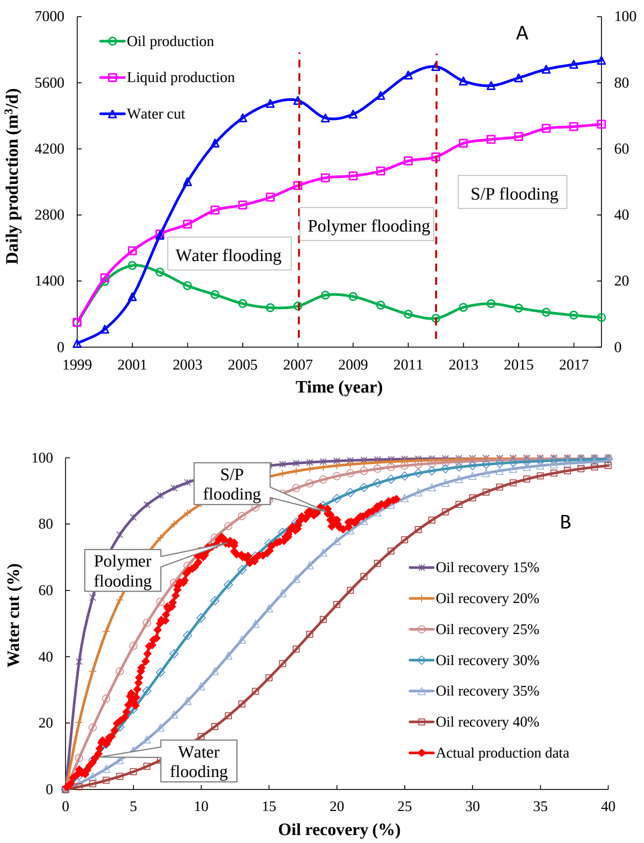

Figure 6. Application of S/P flooding in Bohai H oilfield: (a) Production performance of Bohai H oilfield; (b) Oil recovery forecast template that defined by Tong Xianzhang.

reasonable PV number was 0.3 PV.

The second group scheme was done under injected S/P system solution at 0.3 PV. The schemes include carrying out S/P flooding when the water cut was as follows: 70, 75, 80, 85, 90, 95 and 98%. Figure 5b shows the contrast between the different schemes. The oil recovery increased with increased timing of water cut; higher recovery can be obtained when S/P flooding is carried out at higher water cut period. The numerical simulation result nearly coincides with the laboratory experiment result. It shows the laboratory research results have strong reliability.

FIELD APPLICATION

Water flooding was carried out in Bohai H oilfield during its early development period. The water cut increasing rate was fast. In order to restrain the velocity of water cut increase, polymer flooding method was used in 2007. Polymer flooding scheme design includes injection polymer solution at 0.22 PV. Polymer flooding scheme applied has benefit: the oil recovery increased by 10.5%, but as polymer flooding reached the end stage of the scheme, the water cut increase rate got faster again. According to the research result in this article, the S/P flooding scheme was studied at 0.3 PV when the water cut was 85%. The production well began to improve after the scheme was carried out in 6 months. Every ton of S/P system powder can increase oil by 52 m^3. Figure 6a shows that the production performance was enhanced obviously, and oil daily production increased by about 1.25 times for average single well. Figure 6b shows that by using oil recovery forecast template defined by Tong Xianzhang, the oil recovery of Bohai H oilfield will increase by 4.6%.

Conclusion

(1) In order to improve the production performance of Bohai H oilfield, this article takes reservoir characteristic parameters as reference; the artificial core displacement experiments were conducted based on similarity principle, to demonstrate the feasibility of S/P flooding in offshore oilfield.

(2) S/P flooding method can enhance oil recovery significantly as compared to the polymer flooding or water flooding. Oil recovery can be further increased with increase in injection PV number, but the increase rate becomes slow if PV number is higher than 0.3 PV. Oil recovery also can be increased with increase in injection timing of water cut.

(3) The numerical simulation result is basically consistent with the experiment results. It proved that the laboratory research results have strong reliability.

(4) The production performance improved better. If the research results are applied in actual production of Bohai H oilfield, the oil daily production will increase by about 1.25 times for average single well and oil recovery will increase by 4.6%.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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