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Application of EOR Technology by Means of Polymer Flooding in Bohai Oil Fields

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Abstract

Enhanced oil recovery by means of polymer flooding is considered as an important technology for the strategic development of offshore oilfields in China. The implementation of polymer flooding in the offshore oilfields requires overcoming several major technical problems caused largely by the absence of a fresh water source and limited space on the platform. A pilot test of polymer flooding was conducted in SZ36-1 Oilfield located in Bohai Bay, China. The problems mentioned above were solved through the development of (1) a hydrophobically associating polymer tolerant to salts in the brine and produced water and (2) a portable automatic injection unit. The significant incremental oil and decrement of water cut were observed after 8 months of polymer injection. The successful implementation of polymer flooding makes three breakthroughs: (1) the first polymer flooding pilot test in offshore oilfields in China; (2) initial application of a hydrophobically associating polymer as the driving agent in the field; (3) significant increment of oil in the trail of a single well injection of polymer. The practice illustrates the feasibility of polymer flooding under current production conditions of offshore oilfields that lead to applications in a larger scale.

Introduction

There are about 20 offshore oilfields in Bohai Bay, which are referred to Bohai Oilfields[1], in which 70% crude oil with viscosity ranged from 50 mPa·s to 150 mPa·s. Water flooding is the dominant technique for the development of viscous oil in Bohai Bay. The problem is that the oil recovery by water flooding is quite low 18~20% compared to the average oil recovery of 32% in onshore oilfields. The reasons lie in the high viscosity of the oil, thick pay zones with high heterogeneity, as well as the present offshore oil development mode: the oil is produced normally in an inverted 9-spot flood pattern with 350m well spacing that is much larger than that of onshore oilfields. The operation of the oilfields follows the policy of "less wells with high production rate", which is realized in the limited offshore platforms with a great concern on the investment and balance between production rate and final oil recovery.

SZ36-1 Oilfield, located near the coast of Suizhong County, Liaoning Province, China is a typical offshore oilfield of Bohai Oilfields in reservoir characteristics, fluid properties and development mode. This oilfield was put into operation in 1993. From the very beginning, the technologies on enhanced oil recovery were investigated in order to improve water flooding efficiency. Among the technologies, polymer flooding showed great potential for the oilfield from a study of numerical simulation[2]. It is know that polymer flooding has been successfully used in onshore oilfields like Daqing Oilfield in an industrial scale with an proved incremental oil recovery over waterflooding of 12% OOIP[3]. However, the implementation of polymer flooding on the platform met great challenges on the lackness of fresh water supply and the limited operation space on the platform. Other challenges involved cost, safety, environmental concerns.

The problems mentioned above were solved through the development of (1) a hydrophobically associating polymer tolerant to salts in the brine and produced water and (2) a portable automatic skid injection unit. Based on a series of work on laboratory evaluation and numerical simulation, the first pilot test of polymer flooding was conducted in SZ36-1 Oilfield in September 2003. The purposes of the pilot test were (1) to examine the solubility and injectivity of the polymer under platform conditions; (2) to examine whether the injection facilities meet the requirements of polymer flooding process; (3) to collect produced fluids containing polymers for further study. The pilot test has been conducted successfully with a significant increment of oil. It is followed by another pilot test in SZ36-1 Oilfield. Enhanced oil recovery by means of polymer flooding is considered as an important technology for the strategic development of offshore oilfields in China.

This paper focuses on presenting the challenges for the application of polymer flooding in offshore fields, design of the pilot test including polymer and facilities, and field results of the pilot test.

Field History

The candidate areas for the pilot and further applications of polymer flooding are in SZ36-1 Oilfield. The reservoir was sedimented in a fluvial environment, founded in 1987 and has put into production since 1993 by two phases: Phase I and Phase II. It is a mono-anticline extending in NE direction. The reservoir is structurally controlled and lithologically influenced[5].

Reservoir Characteristics

With stable distribution and good connectivity, the reservoir is distributed in lower Dongying Group with a reversed sedimentary rhythmic feature. The buried depth is in the range of 1300~1600m and average thickness of pay zone is 61.5m. The whole oil-bearing formation is divided into 4 groups, which are subdivided into 14 layers.

Lithologically, reservoir rocks are feldspathic quartz sand composed mainly of fine sands. The sand is unconsolidated and poorly cemented with porosity of 28~35% and average permeability of $2,600\times10^{-3}\mu m^2$. The original reservoir pressure is 14.28MPa and the reservior temperature is about 65°C.

Fluid Properties

Table 1 shows that the properties of crude oil in SZ36-1 Oilfield, which is characterzed as high viscosity high density, low sulphur content, low wax content and high gum and bitumen contents. The density of dead oil is 0.94-0.99g/cm^3 at 20°C. Oil viscosity at reservoir conditions varies from 13 to 380mPa·s with an average of 70 mPa·s. The gas-oil ratio (GOR) is 30-34m^3/m^3 and the formation volume factor is 1.09. The formation water is the type of $NaHCO_3$ with total dissolved solids (TDS) of 6071 mg/L.

Table 1 Properties of the Fluids from the Reservoir of SZ36-1 Oilfield

Fluid	Item	Value
Oil	Density, g/cm^3	0.94~0.99
	Wax, %	2.53
	Sulpher, %	0.35
	Asphalt, %	9.10
	Gum, %	21.9
	Viscosity, mPa.s	70
Water	Bicarbonate, mg/L	2,085
	Carbonate, mg/L	231
	Chloride, mg/L	1,573
	Sulfate, mg/L	146
	Calcium, mg/L	22
	Magnesium, mg/L	14
	Sodium & Potassium, mg/L	2,001
	Total Dissolved Solids, mg/L	6,071

Waterflooding Development

There are 9 wellhead platforms and more than 200 wells for the whole oilfield, which was developed by waterflooding in inverted 9-spot pattern with average well spacing of 350m. **Table 2** shows the compositions of the injection water. Sea water was initially injected for about 8 years. Then water from Guantao Formation was injected. Now the mixture of water from Guantao Formation and produced water is injected. The history of water injection makes the salinity of produced water higher than original formation water, especially in Ca^{2+} and Mg^{2+} ions.

Table 2 Compositions of Injected and Produced Water

Item	Guantao Formation Water	Produced Water	Sea Water
Bicarbonate, mg/L	190	281	171
Carbonate, mg/L	0	114	0
Chloride, mg/L	5,470	9,288	18,168
Sulfate, mg/L	36	317	2,286
Calcium, mg/L	568	281	353
Magnesium, mg/L	228	238	1231
Sodium & Potassium, mg/L	2,552	5,398	10,714
Total Dissolved Solids, mg/L	9,048	16,116	32,423

Since the reservoir rock is unconsolidated and poorly cemented, the wells have been completed with screen gravel pack for sand control in 3 intervals (i.e. Group I upper, Group I lower and Group II). The electrical submersible pumps are used for high-speed development.

By the end of 2003, oil was produced with oil recovery rate of 13.5% and average water cut of 60%. The water breakthrough showed a rapid climb, and water cut of some of the wells reached up to 90%. Reservoir pressure was decreased from the initial of 14.28 MPa to 11.36 MPa, lower than the saturation pressure of 12 MPa. The production turns to decline.

The development effectiveness of waterflooding for the heavy oil reservoir is poor because of the high oil viscosity that causes high oil-water mobility ratio. Moreover, the development of offshore oilfields should be finished within the platform life, usually about 20 years. Limited wells and limited lifetime result in poor recovery. According to the research in overall development program, the oil recovery factor of SZ36-1 Oilfield by means of waterflooding is about 20%.

Pilot Area for Polymer Flooding

In order to improve the effectiveness of waterflooding, a numerical study of polymer flooding for the overall oilfield has been conducted, followed by a pilot test. The pilot area is located in the edge of the oilfield (see **Fig. 1**). It covers approximately 0.396km^2 and contains 1 injector (J3) and 5 coresponding producers (J16, A2, A7, A12 and A13) with an average well spacing of 370m.

Among the 5 corresponding production wells, the communication between J3 and J16 is much better than that between J3 and other oil production wells. As shown in Figure 1, J3 is the exclusive injection well for well J16. It is possible to observe production response in J16 to analyse the effect of the polymer flooding pilot test.

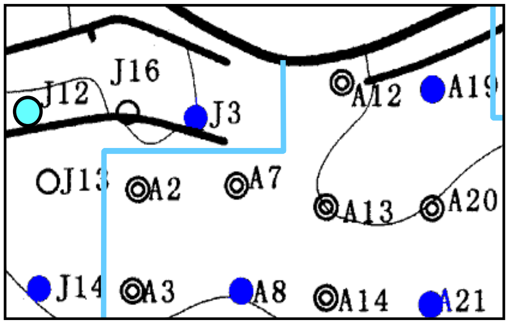

Fig. 1 Location of Wells in the Pilot Area

Polymer System Study

Water Envirenment

To properly design an effective polymer flooding process, water environment is one of the major concerns. In this application, the most feasible choice for water selection of polymer flooding was brine produced on-site from Guantao Formation, since no other practical fresh water source was available. **Table 2** indicates the salinity of the injection water is quite high, especially in divalent calcium and magnesium cations. For years' injection of sea water and water from Guangtao Formation, the main path of the flood has been saturated with high salinity water. The connate water with low salinity present in the formation was not important to exchange the ions in the main path of the flood, which can be observed by the compositions of the produced water. So, it is essential to select a polymer that is tolerant to the actual water envirentment. It also means that conventional anionic polyacrylamide which is very sensitive to the divalent cations could not be applied.

Screening of Polymers

The polymer solutions in Guantao Formation water of more than 10 polymers including commercial partially hydrolyzed polyacrylamide and biopolymer xanthan were evaluated for the polymer flooding process. A hydrophobically associative polyacrylamide, AP-P4 provided by Guanya Science & Technology Co., showed its excellent performances in high salinity environment. Although hydrophobically associative polyacrylamides have been widely reported[6,7], the kind of polymer had not been used in any polymer flooding process by 2003. The polymer properties rely mainly on its viscosity, injectability, longterm stability, and the flooding efficiency. AP-P4 was a brand new polymer that met the challenges for the feasibility to apply it in the field. A series of laboratory evaluation has been conducted.

Laboratory studies

Viscosity – The major purpose of polymer flooding is to augment the viscosity of the injection water, resulting in the modification of poor water/oil mobility ratio. The viscosity of polymer solution is generally required to be greater than that of the crude oil. Some successful applications have been conducted with water/oil mobility ratios ranging from 0.1 to 42. The oil we deal with is the viscous oil with a viscosity of 70 mPa.s. It was hard to have a polymer solution with a viscosity in-situ over the viscosity of the crude oil. However, from our experience, it is not necessary required that the viscosity of the polymer solution is equal to or higher than the oil displaced. According to the equation (1), the oil fraction varies with viscosity of the displacement fluid. In other words, oil fraction will increase with any incremental viscosity of injection water.

$$f_o = \frac{\lambda_o}{\lambda_o + \lambda_w} = \frac{1}{1 + \frac{\mu_o}{\mu_w}\frac{k_{rw}}{k_{ro}}} \qquad (1)$$

Fig. 2 shows the viscosity of AP-P4 solutions with simulated Guantao Formation water under the reservoir temperature. The line with ◆ mark indicates the visicosity without any mechanical degradation, while the line with ■ mark presents the viscosity after the mechanical degredation with Waring Blender to simulate the situation when the polymer solution goes through the perforation into the formation.

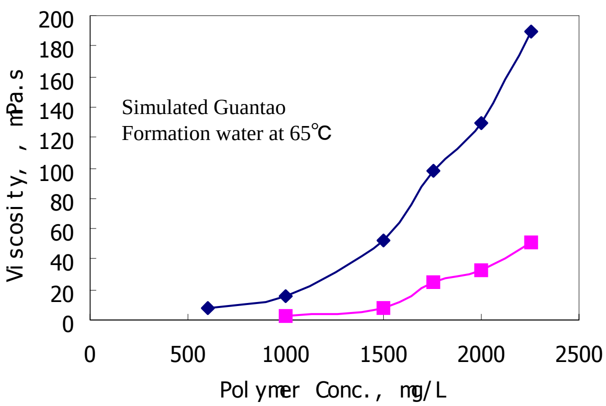

Fig. 2 Apparent Viscosity vs Polymer Concentration of AP-P4 Solutions
◆ Visicosity without mechanical degradation
■ Viscosity after mechanical degredation with Warring Blender

Fig. 2 also illustrates AP-P4 is a good viscosifier for the polymer flooding process in the concentration range from 1,500 to 2,000 mg/L for SZ36-1 Oilfield. Even if after a severe degredation, the solution could keep a relatively high viscosity compared to the commercial partially hydralized polyacrylamides. The concentration of the major slug of the polymer flooding pilot was selected as 1,750 mg/L with a viscosity of 98 mPa.s and a viscosity of 24.5 mPa.s after the degredation.

Injectibility – It is worth to note the solubility of the polymer (hydrophobically associating polyacrylamide) is poor compared to regular polyacrylamides because of the existence of 1-2 mol% of the hydrophobical groups in the main chain. This is one of the reasons why this kind of polymer has not yet been widely used in the fields, even though its viscofier has been known for a long period of time[7]. The problem was overcomed in our work by dissolving the polymer at relatively high concentration and high temperature.

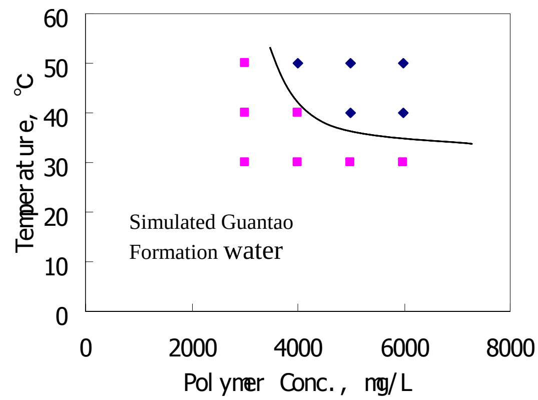

Fig. 3 The Regimes of Fully Disolving ◆ and Partially Disolving ■

Fig. 3 shows the regime of polymer solutions regards to polymer concentration and temperature. Actually, the polymer could dissolve well when its concentration is over 3,500 mg/L and the temperature over 37°C. The dissolved high concentration polymer solution could be diluted to la ow concentration polymer solution (1,750 mg/L, for example), which cannot be obtained by direct dissolution. This indirect proparation process of polymer solution has been applied in the offshore polymer flooding pilot test[8].

Another concern is related with the propagation of the polymer solution in the porous media. A laboratotry test was conducted with a sandpack of 75 cm in length and 3.8 cm in diameter. The permeability and porosity of the sandpack are ,1500 μm^2 and 33.3%. Along with the sandpack, there were 5 pressure measurement points equally distributed. The sandpack was first saturated with water (simulated Guantao Formation Water), then injected with the polymer solution in 1,750 mg/L. **Fig. 4** illustrated the pressure at different measurement points.

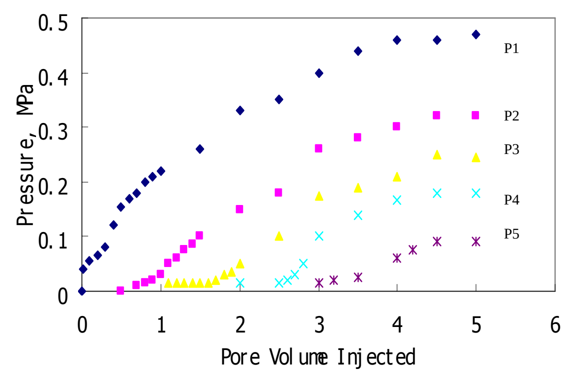

Fig.4 Pressure at Different Measurement Points vs Pore Volume

It can be seen that the polymer solution propagated through the sandpack. There were difficulties to inject the solution. But the fact was the solution was injectable.

Stability - Long-term stability was tested with AP-P4 solution of 1750 mg/L, in which nitrogen was injected in order to displace oxygen in the solution. Figure 5 showed that the viscosity droped dramatically at the first couple of days and then kept the viscosity. The remaing of the visicosity fot 90 days was about 50%, indicating the polymer solution was quite stable at the temperature of 65℃.

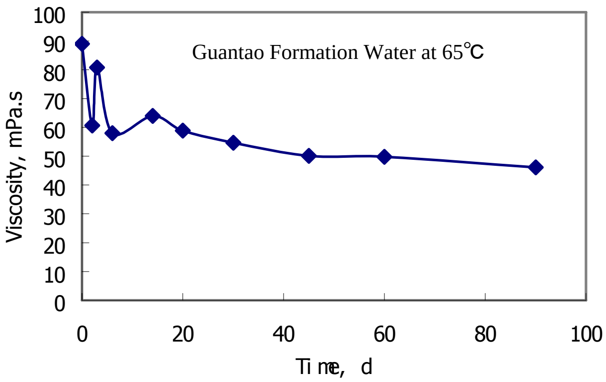

Fig.5 Long-term Stability of AP-P4 at 65 ℃

Core tests – Real cores from SZ36-1 Oilfield have been tested to evaluate resistance factor RF and residual resistance factor RRF. **Table 3** shows the values for the injection of polymer solution without mechanical degradation and that with mechanical degradation using Waring Blender. It seems that the properties of the solution with mechanical degradation is close to reality.

Table 3 RF and RRF

No	ϕ, %	kw, μm^2	RF	RRF	Note
C05-01	33.31	1200	33.31	20.73	No degradated
G19-15	31.29	2586	14.57	2.87	Degradated

Three layer heterogeneous core model with 30 cm in length and 4.5cm ×4.5cm in cross-section were made to test the oil recovery enhanced by polymer flooding[9]. The results showed that with a polymer solution in 1,750 mg/L, if polymer slug is 0.15 PV, the incremental oil recovery was 2.11%, while if polymer slug is 0.225 PV, the incremental oil recovery was 5.05%.

Facilities and Operation

Portable Injection Skid-Mounted Unit - As a result of the platform space limited, the injection facility for polymer flooding in offshore oilfields must be of (1) the smallest horizontal area and space; (2) the least weight; (3) the lowest shearing degradation of polymer and power requirement; (4) the most automatic operation; (5) the longtime secure enough lifetime to run. Furthermore, it is absolutely necessary that, the polymer for displacing agent is able to be dispersed into injected water as quick as possible, the injected rate of polymer solution is much more than that in onshore oilfields and concentration of the concentrate solution is adequately high as well.

According to the mentioned above, major components of the portable injection skid-mounted unit designed and manufactured are shown in **Fig. 6**: (1) mixing tank separating polymer into water rapidly and uniformly; (2) hydration tank in which the initial hydration polymer dissolved completely up to forming solution; (3) static mixer blending the concentrate polymer solution and injected water into polymer driving agent and (4) programmable logic controller that adjusted automatically running parameters of the skid-mounted unit to ensure its normal working.

Polymer Mixing - Powder polymer in the hopper sucked above the mixer tank by a fan and water from Guantao formation of the proper mass ratio are agitated through the top mechanical stirrer in the mixing tank about several minutes, in succession, the mixture are transferred into the hydration tank by the transfer pump fixed between the tubes and stored for 60 minutes around on mixing to get the target concentrate polymer solution of 5,000 mg/L.

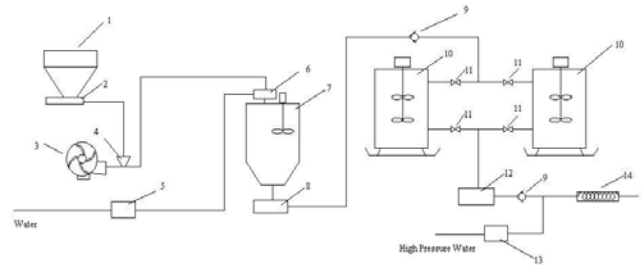

Fig.6 Sketch of the Portable Injection Skid-mounted Unit
1-Feed Inlet; 2-Screw Conveyer; 3-Blower; 4-Material Feeder
5-Flowmeter; 6-Mixer of Water and Powder; 7- Mix Tank
8- Screw Conveyer;9- Single Check Valve; 10-Hydration Tank
11-Valve; 12-Plunger Pump; 13-Flowmeter; 14-Static Mixer

Process of Polymer Injection - The concentrate polymer solution of 5,000 mg/L in the hydration tank is conveyed by the booster plunger pump and converged with the injected water so as to attain the dilute polymer solution of 1,750 mg/L in the static mixer, and then the dilute polymer solution passed through mesh filter is injected into the water input well, finally, it is injected into the pay zone after traversed the wire wrapped screen gravel packing zone.

Results of the Pilot Test

Realization of the goal for the pilot of polymer flooding

Solubility and injectivity of the polymer under platform conditions - As discussed before, hydrophobically associating polymer could be resolved in water with the temperature and salinity above a lower limit. According to the laboratory data, with the high salinity of the injected water, the lowest solution temperature of AP-P4 used in SZ36-1 is above 35°C. The temperature of the injected water in the field is above 37°C~42°C, which is suitable for the resolution of the hydrophobically associating polymer. The actual visicosity of the polymer solution varied from 60 mPa·s to 100 mPa·s, indicating that the polymer powder dispersed and resolved in the solution to enhance the viscosity of the injected fluid in the limited time (2 hrs). No “fisheye” was found and the injection pressure kept stable. This meant there was no wellbore plugging due to the polymer injection.

Requirements of polymer flooding process - During the whole period of polymer injection, about $500m^3/d$ polymer solution was injected continuously into Well J3 at the injection pressure of 6~8MPa. The facilities run in security during the whole process of the injection.

Polymer solution obtained from corresponding wells - Produced polymer could increase the difficulity of water disposal and oil processing. Polymer in produced fluid would emulsify the water and the oil so greatly that the treatment procession would fail to produce an acceptable result. The situation would become severe as abundant polymer is produced at the late stge of the polymer flooding. Therefore, treatment of produced polymer would become a technical chanllenge for offshore application. Produced fluids containing polymers were collected and analysed in the pilot test. A peak value of 200 mg/L polymer had been inspected on Well A7.

Response of the corresponding wells

(1) Injection pressure built up in the initial stage of the flooding. At the beginning of the injection, the pressure in the injectior Well J3 increased greatly due to the variation of water viscosity. On Well J3, the water injection rate before polymer injection was about $500m^3/d$ at a wllhead pressure of 2~3MPa. A rapid increase in pressure was observed immediately after the polymer injection. And it reaches a maximum pressure at 7~8 MPa within a month, then kept pressure

throughout the polymer injection process. The injection rate was stable at about 500m^3/d, indicating no plugging occurred.

(2) Fluid productivity reduction in the front stage of the flooding. The viscosity of the polymer increased the flow resistance of the fluid, reducing the velocity of the injected water towards the production well. The fluid production of Well A7, for example, was over 250m^3/d before the pilot test, decreased to 200m^3/d after the polymer flooding, and reached to the lowest point at 140m^3/d in Feb. 2005. The producing fluid level of the Well A7 went from 320m to 500m, before and after the polymer flooding respectively. Production reduction and producing fluid level decline could also be observed in other correspondent wells. The fluid productivity tended to be stabilized when polymer solution achieved adsorption equilibrium in the formation.

(3) Incremental oil production and decrease of water cut. The polymer would improve mobility and areal sweep of the injected fluids, resulting in the increase of oil production rate and decrease of water cut. In the initial stage of the polymer injection, production profile maintained the previous trend of continous rise in water cut and decline in production rate. Taking Well J16 as an example, it produced less than 20m^3 per day with water cut of 95% before the begginning of the pilot test. The production rate continued to maintain at a low level in the next several months until Aug. 2004, 10 months later since the polymer injection. An obvious response of polymer flooding was observed in Well J16, with oil production sustainable growth to 70m^3/d and significant water cut drop to 54%.

(4) Retardant response of production due to larger well spacing. It took over 10 months for Well J16 to begin showing a response of polymer flooding. Oil wells other than J16 in the pilot area didn't show a distinct response even after the injection stopped in May. 2005. It was estimated that only 0.03PV of polymer solution was injected in the target formation in the 20-month test, quite few than the amount of 0.1~0.2PV, lower limitation needed for a polymer flooding to show a response according to the previous experience. With the same injection rate, larger well spacing resulted in lower flowing pace of polymer solution, taking longer time to accumulate to a certain amount of PV. The distance between Well J3 and Well J16 is much smaller than that between Well J3 and any other corresponding oil wells. That is one of the reasons for Well J16 to have an earlier response compared to the other wells in the pilot area. It is anticipated that the actual response of polymer flooding in SZ36-1 Oilfield was longer than expected.

Incremental oil - Incremental oil production showed markedly in well J16 (**Fig. 7**). By the end of Feburary 2006, 23,000m^3 of accumulative crude oil has been produced in well J16 with no natural decline was counted. The composite water cut of the well group reduced from 66% to about 50%. It was proved that polymer flooding would be a feasible approach for production stimulation in SZ36-1 oilfield.

Conclusions

1. The first offshore polymer flooding pilot test has been implemented in Bohai Oilfields in China, followed by 2 more polymer flooding pilot test, showing the trend of the development of EOR technologies in the offshore oilfields in China.
2. The successful implementation of offshore polymer flooding pilot test depends on the development of (1) a hydrophobically associating polymer tolerant to salts in the brine and produced water and (2) a portable automatic injection unit.
3. The significant increment of oil in the trail of a single well injection of polymer proved the feasibility of polymer flooding under current production conditions of offshore oilfields, which will lead to applications in a larger scale.

Nomenclature

GOR = Gas-oil ratio
TDS = Total dissolved solids
OOIP = Original Oil in Place
EOR = Ehhanced oil recovery
f_o = Oil fraction
λ_o = Oil mobility
λ_w = Water mobility
μ_o = Oil viscosity
μ_w = Water viscosity
k_{ro} = Relative permeability to oil
k_{rw} = Relative permeability to water
ϕ = Porosity
RF = Resistance factor
RRF = Residual resistance factor
PV = pore volume

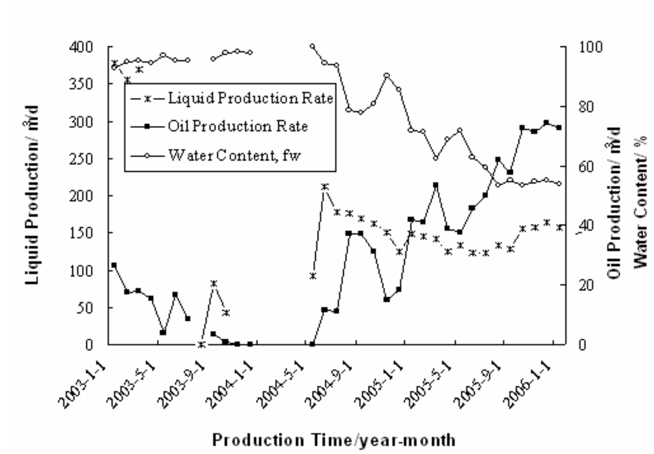

Fig.7 Production Rate vs Production Time

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