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Application of Hydrophobically Associating Water-Soluble Polymer for Polymer Flooding in China Offshore Heavy Oilfield

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Abstract

Polymer flooding is one of the most important EOR technologies currently producing substantial oil increment in China onshore oilfields. The application of polymer flooding in the offshore environment is more complex and face to many technical challenges due to the absence of the fresh water source and limited space on the platform. Compared to regular anion polyacrylamide mostly used in onshore oilfields, hydrophobically associating water-soluble polymer (HAWP) could keep relatively high viscosity in the high salinity brine. A kind of HAWP was introduced in the first pilot test of polymer flooding conducted in SZ36-1 oilfield of Bohai Bay, China. The single injector pilot test was applied successfully, obtaining 2,5000m^3 incremental oil in the corresponding production well and water cut decreased from 95% to 54%. It indicates the technical effectivity of HAWP used as a driving agent in the high salinity heavy oilfield. A scale up test has been conducted in the well group and the same polymer has been employed. The corresponding wells have showed a good response and produced 12,000m^3 incremental oil up to the Feb. 2007. Meanwhile, the produced fluid containing trace of HAWP has been collected for evaluation of its influence on the offshore production system. The tests showed the feasibility of HAWP for offshore polymer flooding and provided experience for its further application.

Instruction

Oil production in China offshore oilfields increased significantly with the more and deeper research on exploration. It is estimated that around 70% of oil reserve in China offshore oilfields are heavy oil, and 64% of them are discovered in Bohai bay. Currently the oil recovery by water flooding is only 18 – 25%, which is far below than that of the onshore the average oil recovery of 32 –40%. Assuming that recovery rate for Bohai heavy oil reservoir with 2.4×10^9t reserve improves 1% shows that there is approximately an additional hurdred million-class oil reservoir to be produed, which will make a significant contribution to the longevity of the Bohai oilfields, and realize the low input and high rewards of development of oilfields.

Polymer flooding for enhanced oil recovery has been proven both technical and economic feasibilities in China[1]. It is used to reduce the local remaining oil saturation by changing the fractional flow curve and to improve sweep in the less permeable zones. As a driving agent, polymer reduces the mobility of aquifer phase to force the remaining heavy oil. Moreover, it has the advantage that it is not require complex and additional surface equipments for polymer flooding in the relatively limited platform area. However, for a successful polymer flooding, it faces five main challenges for its application to offshore heavy oilfields.

1. High salinity and hardness of the make-up water (Ca^{2+} and Mg^{2+}: 600 – 1,200mg/L), and high viscosity of oil (in average of 70mPa·s), which require the polymer to be salt resistant and good viscosification.
2. Limited spacing of platform does not allow big volume installation for polymer resolving, so development of fast-resolving polymer is necessary.
3. Drilling and completion by wire wrapped screen gravel-packed sand control and large displacement of offshore oilfields require strong anti-mechanical degradation ability of polymer.
4. Long-term stability of polymer in the formation is required because of the large well spacing and thick pay zone.
5. Treatment of produced fluid to meet the environmental requirements should fast and complete in the platform. So the effect of polymer to the produced fluid should be considered in the polymer design.

Partially hydrolyzed Polyacrylamide (PHP) is a long chain high molecular weight polymer with great visocification, and commonly used in the enhanced oil recovery process. However, it is sensitive to the high salinity and hardness of make-up water or formation water in offshore oilfields, which makes the viscosity of PHP solution decreased greatly in general. For those reasons, a kind of HAWP is being designed and synethesized with less sensitive to sanility and high viscosification as a driving agent for offshore polymer flooding. It is similar to conventional water-soluble polymer except that a very small portion of hydrophobic comonomer (<1%) is incorporated into the polymer backbone[2]. Above the overlap concentration, these polymer chains associate intermolecularly in solution, significantly increasing hydrodynamic size and inherent visocosity. This is of great importance in enhanced oil recovery.

Characteristics of Hydrophobically Associating Water-soluble Polymer (HAWP)

Overcoming the five main challenges is crucial for a successful offshore polymer flooding. In this paper, HAWP is discussed and shows its characteristics satisfying the requirement of offshore operation.

Vicosification

The use of water soluble polymers to increase the water viscosity has been shown to be an effective way to improve the sweep efficiency and hence increasing the oil recovery. To investigate the viscosification of HAWP, a make-up brine for injection to J3 well of SZ36-1 oilfield, Bohai Bay with the salinity of 9048mg/L was used in the test. The experimental result shows that visosocity of HAWP increased significantly with the increase of concentration of polymer solution. As shown in Fig.1, the overlap concentration C* appeared on the polymer concentration of 1500mg/L. When polymer concentration was lower than C*, intra-action of polymer molecules was dominant, and polymer chains were highly coiled. As a result, viscosity increases slowly with the increase of polymer concentration. When polymer concentration is close to, even higher than C*, intermolecular associations emerge and become strong, resulting viscosity increased sharply with the increase of polymer concentration.

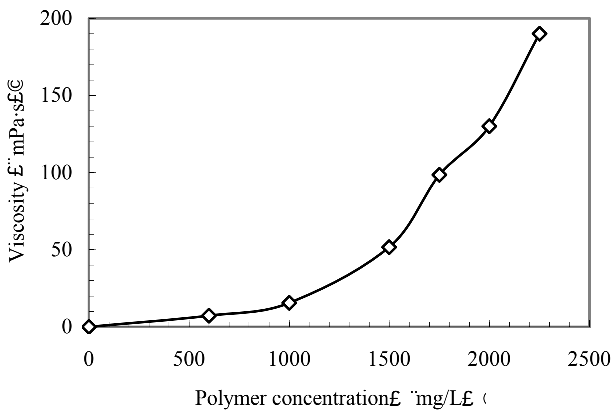

Fig.1 Viscosity of HAWP vs. HAWP concentration

Solubility

Because there is a small portion of hydrophobic comonomer introduced into HAWP, the resolving of HAWP become conditional. Fig.2 shows the effect of temperature and polymer concentration on the solubility of HWAP. There is a critical resolving temperature for HAWP about 37^{o}C, i.e., HAWP would not resolve below this temperature even increasing the polymer concentration. Meanwhile, it has been found that when polymer concentration is over than 5000mg/L, polymer would resolve in 1h at the temperature of 50^{o}C. Comparatively it should take 2h to resolve at 40^{o}C. Experimental result shows higher polymer concentration and higher temperature are favorable for the resolving of HAWP.

At the platform conditions, a well-designed equipment for polymer dissolution is necessary. In the field applications, the uniformed high concentration of polymer stock solution firstly is prepared at 37 ~ 40^{o}C, then diluted it to the desired concentration of solution.

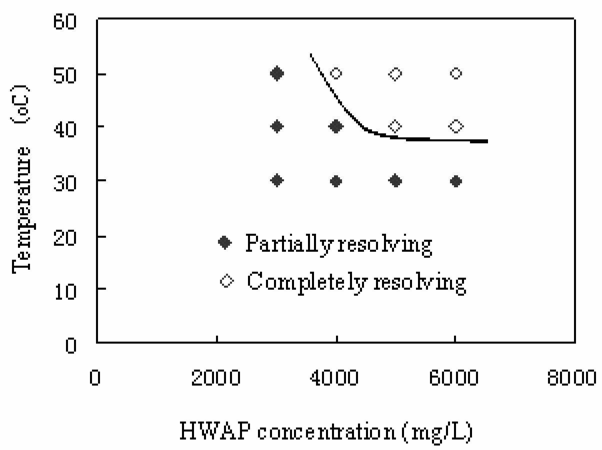

Fig.2 Effect of temperature and polymer concentration on HAWP solubility

Mechanical degradation

It is known that when a polymer solution is exposed to high shear conditions the molecule may be scissored. High shear conditions occur during mixing of polymer solutions, or during the conveyance of a polymer solution in pumps and chokes, or during injection in perforations, or in the formation near the well bore where the polymer solution is flowing at high velocities[3]. Fig.3 shows that the viscosity of HAWP decreased sharply after shearing. But this sensitivity of mechanical degradation is not so serious for HAWP to be excluded from being used for enhanced oil recovery. The remained viscosity was about 25mPa·s under polymer concentration of 1750mg/L, which could guarantee the good mobility in the formation after polymer flowing through the surface facilities and other high shear conditions.

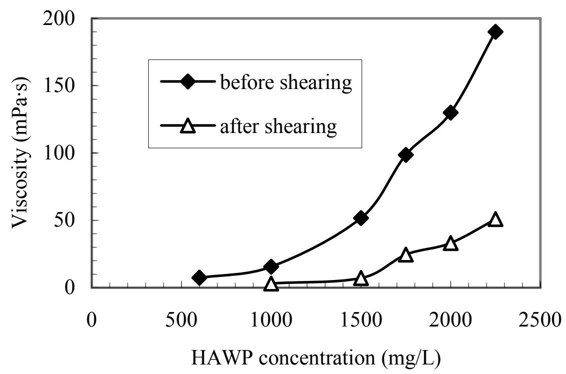

Fig.3 Effect of shearing on HAWP viscosity

Long-term thermal stability

Normally a polymer flooding project would last for years, which requires polymer stable throughout these long periods. When polymer solution is kept for a longer period at high temperature, it can degrade and lose its viscosity. Long-term thermal stability is measured under the condition of free of oxygen. In this test, pure nitrogen has been injected into 1750mg/L HAWP solution at 0.01MPa for 20min, then the glass tube contained polymer solution been sealed, and put in a temperature control device at 65°C. Viscosity losses at different time were measured and the experimental results were showed in Fig. 4. In the first three days, viscosity lost quikly from 875mPa·s to 390mPa·s. Then visocosity is kept stable, and 59.7% of original viscosity was remained after 90 days, which indicates that HAWP had good long-term thermal stability.

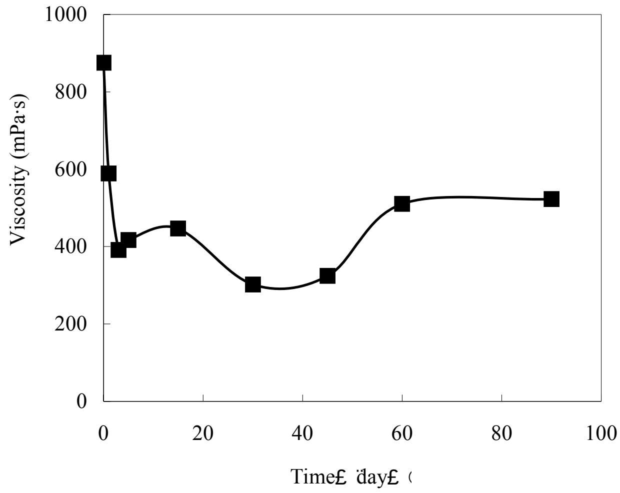

Fig. 4 HAWP visocosity vs. time at 65°C

Treatment of produced fluid contained HAWP

Treatment of produced water is one of the important issues for a successful polymer flooding project in offshore oilfield. Produced fluid containing polymer should be treated in the limited spacing of platforms, while meeting the requirement of reinjection to the well or discharge to the sea. Because of the existence of polymers, the contained oil in the produced water increased a lot, which would lead to the hard demulsification and increamental of viscosity of produced fluid. Many researchers have been investigated on this topic and have been tried various methods, including mechanical, chemical, and heating, etc. to solve the problems, but still can not find the best way[4,5,6].

At the early stage on the investigation of treatment of produced fluid containing polymer, foundamental research has been conducted and made some progress. A new demulsifier and assitant-demulsifier for offshore application has been developed to dehydrate water from the oil-water emulsions[7,8]. Fig. 5 showed the effect of HAWP concentration on the water content of crude oil after treatment with the demulsifier. The results indicated that when HAWP concentration in the produce water was lower than 110mg/L, the water content of crude oil would be dehydrated to as low as 1% and meet the requirement of transportion. Meanwhile, the synergestic effect of demulsifer and assitant-demulsifer would effectively reduce the content of oil and suspended solid in the produced water as showed in Fig. 6. Though some progresses have been achieved, there is a lot of research work has to been done on this field to meet the requirement of platform operation.

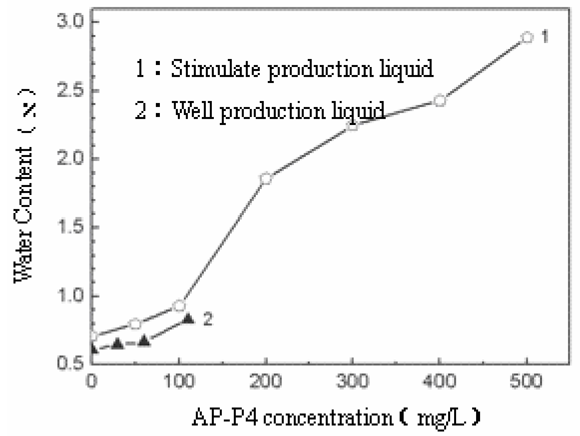

Fig. 5 Effect of HAWP on water content of oil after treatment with demulsifier

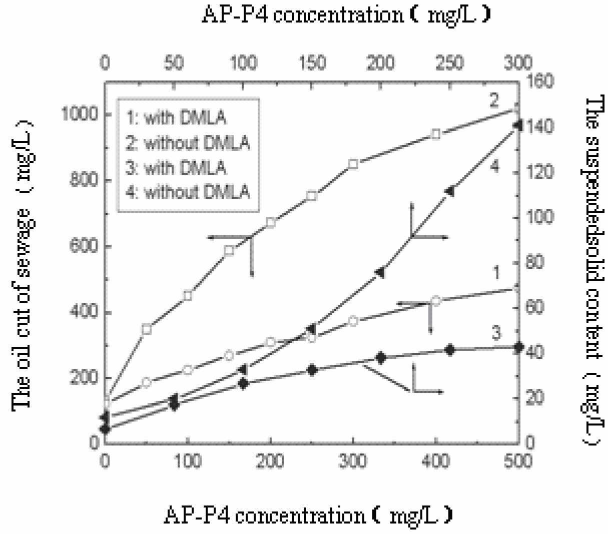

Fig.6 Effect of HAWP on content of oil and supended solid of produced liquid

Field Applications

SZ36-1 oilfield

SZ36-1 oilfield is located at the coast of Liaodong, Bohai Bay, China[9]. With stable distributioed and good connectivity, the reservoir is distributed in lower Dongying Group with a reversed sedimentary rhythmic feature. Lighologcially, reservoir rocks are feldspathic quartz sand composed mainly of fine sands. It was put into operation since 1993. From the very beginning, the enhanced oil recovery technologies were taken into consideration, and polymer flooding showed great potential among these technologies[10]. Reservoir characteristics of SZ36-1 oilfield were given in Table 1.

The crude oil in SZ36-1 oilfield is highly viscous, varied from 13 to 380mPa·s, with an average of 70mPa·s at reservoir conditions. It is characterzed as high desity, low sulphur content, low wax content and high gum and bitumen contents. The detailed properties of oil were concluded in Table 2.

HAWP has better performance on high salinity water than conventional water-solulbe polymers. Sea water with high salinity of 32,423mg/L was initially injected for about 8 years. Then water from Guantao formation with salinity of

9048mg/L 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 that of the original formation water, especially of Ca^{2+} and Mg^{2+}. The composition of make-up water for different stages of SZ36-1 oilfield development was listed in the Table 3.

Table 1 Reservoir characteristics of SZ36-1 oilfield

Depth, m	1300 ~ 1600
Average pay thickness, m	61.5
Porosity, %	28 ~ 35
Average permeability, $10^{-3}\mu m^2$	2600
Original reservoir pressure, MPa	14.28
Reservoir temperature, °C	65

Table 2 Oil properties of SZ36-1 oilfield

Density, g/cm^3, 20°C	0.94 ~ 0.99
Viscosity, mPa·s	13 ~ 380
Gas-oil ratio (GOR), m^3/m^3	30 ~ 34
Formation volume factor	1.09
Wax, %	2.53
Sulpher, %	0.35
Asphlat, %	9.10
Gum, %	21.9

Table 3 Composition of make-up water for SZ36-1 oilfield

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	1,231
Sodium & Potassium, mg/L	2,552	5,398	10,714
Total Dissolved Solid, mg/L	9,048	1,6116	32,423

Single well pilot test

J3 well of SZ36-1 oilfield was chosen for the first single well pilot test by using HAWP in China offshore fields. After injection of HAWP for 10 months, water cut decreased and oil production increased in the corresponding wells. The accumulated oil reached 25,000m^3 and water cut decreased from 95% to 54% until the end of the test. This test shows that HAWP as a high efficient driving agent, successfully conducted in the single well pilot test, which was the solid foundation and provided usful experience for the further field tests. The more detailed description for the single well pilot test was refered in the previous paper[9].

Well group pilot test

The success of single well pilot test provided foundamentals for the well group pilot test. In addition, single well test proved the successful application of HAWP to offshore oilfield. So HAWP was choosen for the well group pilot test. Throughout the deep research on the condidate reservoirs, pilot area was decided with a five-spot pattern. It covers 0.965km^2 with the primary geologic reserves of 645.8×10^4m^3. The center well area is 0.215km^2 with the primary geologic reserves of 155.3×10^4m^3.

Since October 2005, polymer flooding for well group pilot test has been carried out. The project is designed to continuous inject HAWP for 3 years (i.e., 0.172 Pore Volume), and the total polymer consumed 3,142.7tons (see Table 4). According to the injection history from Oct.30, 2005 to Feb.28, 2007, the four injection wells injected polymer solution 69.8×10^4m^3 (i.e., 0.067 Pore Volume), and polymer consumed 1,168tons. The whole operation was stable as expected.

After injection of HAWP 6 months, water cut began to reduce, and oil production increased, as Fig. 7 shows. Until Feb. 2007, the total incremental oil by polymer flooding reached 12,000m^3, and total production kept stable.

Produced polymer is monitored since the beginning of the test. From the end of 2006, there were trace of produced polymer was measured from the corresponding wells. Unfortunately, there is not much data available since then.

Table 4 HAWP consumption for well group polymer flooding project.

Stock solution Con. (mg/L)	Injected Con. (mg/L)	Injection rate (m^3/d)	Total injection (10^4m^3)
5,000	1,750	1,640	179.58

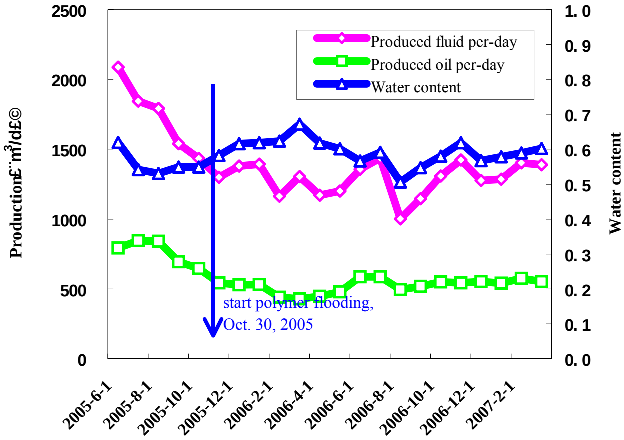

Fig. 7 Production curves of well group pilot test

Conclusions

1. Offshore polymer flooding is more difficult than onshore polymer flooding because of specific offshore conditions. Characteristics of hydrophobically associating water-soluble polymer (HAWP) aimed to the requirement of offshore operation were investigated. The results showed HAWP had good performance on high salinity water and on platform conditions.
2. HAWP was firstly introduced to the single well test in SZ36-1 oilfield, and achieved 25,000m^3 incremental oil. It indicates that as a driving agent, HAWP is feasible from the technical point of view.
3. The conducting well group test by HAWP has shown the trendency of incremental oil and decremental water cut.
4. HAWP has been proven suitable for the offshore polymer flooding, which provide the prospective for its further application on other offshore oilfields.

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