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Current Developments and Remaining Challenges of Chemical Flooding EOR Techniques in China

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Abstract

Chemical flooding EOR techniques, mainly including polymer flooding, chemical combination flooding and foam flooding, play a crucial role in Chinese oil industry. Field tests proved that chemical flooding EOR techniques could be applied successfully in onshore reservoirs in China. Challenges were also presented as the chemical flooding EOR were applied in different reservoirs. The current developments of chemical flooding EOR techniques were introduced, the chemical flooding field tests were summarized and remaining challenges were discussed in this paper.

Polymer flooding has entered into commercial applications stage. By the end of 2011, 54 industrial blocks of polymer flooding have been applied in Daqing Oilfield with 13% incremental oil recovery over water flooding in average. Ten key techniques for polymer flooding have been developed involving polymer screening and evaluation, low viscosity loss facility of injection, high performance polymer preparation and injection equipments and crafts, eccentrically-wearing inhibiting technology, separated layer injection etc. Chemical combination flooding especially ASP flooding has been studied and tested intensively in China. Six pilot and four industrial field tests of ASP flooding have been implemented. More than 20% incremental oil recovery after water flooding has been obtained. A set of techniques for combination flooding have been formed such as ASP formulation optimizing, injection allocation technology, lifting technology, chemicals monitoring of produced liquid etc. Twenty foam flooding pilot tests have been carried out in China, and sixteen of them showed good performances.

Challenges of polymer flooding are mainly focused on the development of new effective polymers for specific reservoir conditions such as high salinity, high temperature, and low permeability reservoirs. The limitations of ASP flooding were known as the scaling problem and difficulty in produced liquid treatment. Challenges in foam flooding were mainly the gas finger problem usually occurred in field tests. Some progresses have been made in recent research and shown good perspectives.

Introduction

Most oilfields in China are characterized with continental sedimentation. The heterogeneity of reservoirs is very high. The developed reserves with water flooding account for more than 85% of the overall geological reserves. The main water flood oilfields have entered the high water cut and high recoverable recovery stage. By the end of 2010, the average water cut of main oil fields in China has reached 87%. The average recoverable recovery of main oil fields in China has reached 76%, whereas the average recovery factor is only around 33%. The oil production from high water cut oilfields accounts for 60% of the overall production. Furthermore, many high water cut oilfields have been developed for a quite long time (several decades). Generally, the residual oil distribution is highly dispersed and is difficult to be recovered. Problems such as preferred flowing channels caused by water injection in heterogeneous reservoirs lead to ineffective circulation of injection water, which pose great difficulty for development adjustment and recovery enhancement. Overcoming such problems brings new challenges and opportunities in the process of sustainable development of energy in China.

EOR potential was evaluated in more than 200 onshore oilfields located in 17 different oil reserved districts in 1999. The results showed that China has great EOR potential[1] (Table 1). The estimate of incremental recoverable reserves was accumulated up to 1.18 billion tons based on the technically recoverable resources (TRR) and EOR values by different EOR methods. The chemical flooding (polymer flooding, alkali-polymer flooding and alkali-surfactant-polymer flooding) covered 5 billion tons. It accounts for 76% of the overall EOR covered reserves (shown in Fig. 1). Therefore, chemical flooding showed a vast potential to increase oil recoveries and was the major EOR method in China. Through continuous technique innovations and persistent tackling with bottle-neck technologies, the target of annual oil production over 13 million tons before 2016 by chemical flooding EOR can be realized and the gradual increase of crude oil production of China can be achieved.

Table 1—Results of EOR potential estimated for onshore oil fields in China

EOR techniques		TRR(10^6 tons)	EOR(%)	reserves (10^6 tons)
Chemical EOR methods	Polymer flooding	2,905	9.7	282
	Alkali-Polymer flooding	141	13.1	18
	Alkali-Surfactant-Polymer flooding	3,127	19.2	600
Gas EOR methods	Gas (miscible) flooding	525	18.2	95
	Gas (immiscible) flooding	702	8.7	61
Thermal EOR methods	Cyclic steam stimulation (CSS), Steam flooding (SF)	574	22.2	128
Total		7,974		1,184

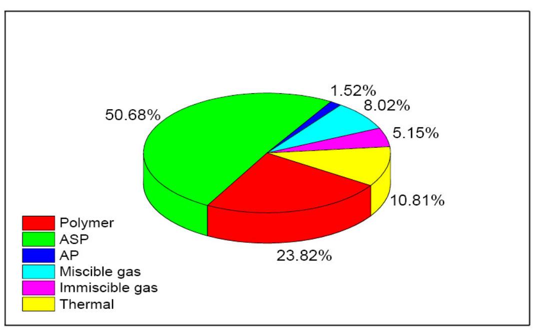

Figure 1—The estimate of covered reserves proportion of different EOR methods

With the rapid development of chemical flooding technologies during recent decades, chemical flooding has become the major EOR method of medium and light oil production in sandstone reservoirs in China. Polymer flooding has entered into commercial applications stage. By the end of 2011, 54 industrial blocks of polymer flooding have been applied in Daqing Oilfield with about 13.0% (OOIP) incremental oil recovery factors over water flooding in average. Pilot tests of chemical combination flooding have been carried out in Daqing, Shengli, and Xinjiang oilfields. The test results showed that chemical combination flooding could significantly increase oil recovery. The incremental oil recovery factors of five pilot tests of chemical combination flooding in Daqing Oilfield were more than 20% (OOIP). The pilot test carried out in the conglomerate reservoir of Karamay Oilfield was also successful[2]. By 2016, chemical combination flooding will replace polymer flooding as the major EOR technique in China with technical bottle-neck problems being overcome.

From 1994 to 2012, twenty foam flooding pilot tests were conducted in China. Most of the them gained favorable EOR performances[3]. Even through, there are still some limitations remained in the technique. In any case, foam flooding has potential to be applied in increasingly complex reservoir conditions.

This paper summarized the progress of polymer flooding and ten supporting technologies based on a successful field experience. The research progress and performance of chemical combination flooding field tests were introduced. The pilot tests of foam flooding were also reviewed. Finally, the remaining challenges and development trend of chemical flooding technologies were discussed.

The Development and Present Situation of Polymer Flooding Technique

The development process and application situation of polymer flooding

The indoor polymer flooding research was started in 1965 in China. Researchers showed an increased displacement fluid viscosity by adding the water-soluble high molecular weight polymer, resulting in a decrease of mobility ratio of solution to oil thereby improving the sweep efficiency. Pilot tests of polymer flooding were started in 1972 in Daqing Oilfield. In the well group of Pu I_{1-4} single strata polymer flooding test, the water cut decreased from 95.2% to 79.4% and the oil production increased from 37 tons to 149 tons per day. Polymer flooding enhanced oil recovery by 14% (OOIP) after water flooding. The overall recovery factor reached to 52.2% (OOIP)[4]. Based on good results of pilot tests, Daqing Oilfield started polymer flooding industrial tests in 1991. In the well group of Pu I_{1-4} strata of block North-1 polymer flooding test, the test area was 3.13 km2 with geological reserve of 6.32 million tons. The number of injection and production wells was 61. The water cut in test zone decreased from 90.7 % to 73.9 %. The oil production per day increased from 651 tons to 1,357 tons. The polymer flooding can increase oil recovery by 13.62% (OOIP) after water flooding. Each ton of polymer could increase oil production by 130 tons[5]. The polymer flooding efficiency has been significantly increased with the improvement of polymer product property and the development of injection and production technologies.

Commercial application of polymer flooding started from 1996 in Daqing Oilfield. By December in 2011, polymer flooding has been applied in 54 blocks in Daqing Oilfield with industrial scale. The target geological reserves were 756 million tons. The parameters and results of industrialized polymer flooding in three typical blocks type?high permeability reservoir are summarized in Table 2. With the increase of injection pressure of polymer flooding, injection profile was adjusted and sweep efficiency was improved compared with water flooding. The average enhanced oil recovery beyond water flooding of these three blocks was 13.6% (OOIP). The water cut curves of central wells in six blocks of Daqing Oilfield were shown in Fig. 2. The varied regularity of water cut with injection volume of six blocks in central wells was basically the same. Water cut decreased firstly and then kept stable and finally increased again. Compared with other wells, decreasing amount of both central wells in N1E and N2E were larger with water cut as low as 70%.

Table 2—Parameters and results of industrialized polymer flooding in three typical blocks type I reservoir

projects	Well spacing (m)	Injection rate (m3/d·m)	Concentration of polymer (mg/L)	Injection Pressure (MPa) Water flooding	Injection Pressure (MPa) Polymer flooding	ΔP	EOR (%)
DQ-N1	250	15.6	832	5.5	11.3	5.8	12.9
DQ-L1	212	11.5	1,002	5.2	12.9	7.7	13.8
DQ-X5	200	11.2	1,207	6.5	11.1	4.6	14.1
Mean	220	12.8	1,013	5.7	11.8	6.1	13.6

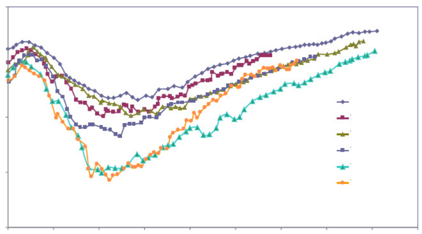

Figure 2—Water cut curves of center wells in six polymer flooding industrialized blocks

The industrial scale and EOR performance of polymer flooding in Daqing Oilfield are summarized in Table 3. The accumulated oil production by polymer flooding has achieved 108 million tons. 118.7 tons of crude oil could be produced with one ton of polymer. The economic benefit is obvious. At present, polymer flooding has been extended and applied in Liaohe, Xinjiang and Dagang Oilfield. The target reservoir type by polymer flooding has extended from high permeability sandstone reservoirs to intermedium and low permeability sandstone reservoirs, conglomerate reservoirs and complex fault block reservoirs[6]. The parameters and results of industrialized polymer flooding in intermedium permeability type II reservoir in Daqing Oilfield are summarized in Table 4. The average enhanced oil recovery beyond water flooding of these four blocks was 12.3% (OOIP).

Table 3—Scale and EOR performance of industrial extended application of polymer flooding

No.	Items	Amount
1	Number of blocks	54
2	Employed geological reserves (tons)	7.56×10^{8}
3	Number of wells	12,426
4	Polymer consumption (tons)	91×10^{4}
5	Accumulative total oil production (tons)	1.08×10^{8}
6	Incremental oil production (tons)	66.78×10^{6}
7	Oil production by one ton of polymer (tons)	118.7

Table 4—Parameters and results of industrialized polymer flooding in three typical blocks type II reservoir

Projects	Effective thickness (m)	Effective ermeability (mD)	Well numbers (injector/producer)	Well spacing (m)	Injection polymer volume (mg/L·PV)	EOR (%)
DQ-N1-A	12.0	565	75/99	175	1,012	10.7
DQ-N1-B	16.1	629	87/121	175	1,001	14.9
DQ-N1-C	9.2	462	230/237	150	1,146	11.3
DQ-L-A	9.8	582	170/223	150	1,565	12.4
Mean		560			1,181	12.3

The integrated techniques of polymer flooding

The polymer flooding technique was improved continuously in the process of industrial extended applications. Till now, the integrated techniques concerning reservoir engineering, oil production engineering, surface engineering and dynamic monitoring in field tests of polymer flooding have been formed based on a series of successful field experiences.

Polymer screening and evaluation The polymer quality evaluation standard including eleven testing indexes and evaluation methodologies have been established[7]. Polymer should be screened and chosen based on the target reservoir conditions. The polymer product quality for pilot tests and application should be strictly controlled thereby guaranteeing the performance of the tests. The present study showed that the viscosity, resistance factor (RF) and residual resistance factor (RRF) of polymer solution in porous medium were proportional to polymer molecular weight. However, as the polymer molecular weight is too high, injection problems might occur in low permeability reservoirs. The optimal polymer molecular weight for different reservoir permeability was studied in Daqing Oilfield (Fig. 3). Polymer molecular weight of 25 million could be used for reservoir with permeability greater than 200 mD, whereas only polymers with molecular weight less than 15 million could be used for reservoirs with permeability less than 150 mD.

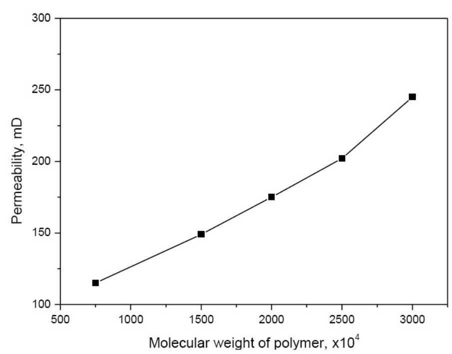

Figure 3—The matching relationship between polymer molecular weight and reservoir permeability

Project design and numerical simulation Each polymer flooding test and application will go through project design processes including geological analysis, reservoir description, series of strata combination, well pattern and spacing optimization and injection parameter optimization. Polymer flooding simulation platform POLYGEL has been developed and applied to optimize the plan of polymer flooding.

Well completion technology under low shearing rate Well completion craft was improved through optimization of perforation bullet and perforation process parameter to inhibit the shear degradation of polymer when polymer solution passes through the shot hole.

High performance preparation and injection facilities There are many problems in high molecular polymer solutions preparation and injection craft during field tests, such as the unstable concentration of mother liquid of some of high molecule weight polymers, the large deviation of prepared concentration, and the extended ageing time. To overcome those drawbacks, the disperse equipment with rotational flow and degasification ability, the stirrer with double screw and mother liquid filter with regeneration filter core were developed. The preparation and injection craft and injection technology for high molecular weight polymer was developed. The dissolving and aging time was shortened. The accuracy of solution preparation process was improved. The construction investment of injection allocation station was decreased by 25%. The maintenance of the operating cost was decreased by 10%[8]. In order to solve the degradation problem caused by the eccentric water distributor, the concentric separated injection technology was developed. The injection pressure could be adjusted by concentric water distributor to inhibit the degradation of polymer solution. The viscosity loss rate of polymer solution was less than 5%.

Separated layer injection technology When a layered reservoir has a large permeability contrast in vertically different layers, separated layer injection of polymer flooding can solve the interlayer contradiction and increase the injection strength in poor layers. Thus the overall technology and economic performance of polymer flooding could be improved. When the permeability ratio of the interlayer was higher than 2.5, separated layer injections of polymer flooding can increase the oil recovery by 2% in contrast to the general injection[9]. Based on the theory and practice, the principle employed by separated layer injections of polymer flooding was proposed as follows: firstly, the permeability ratio of the interlayer was equal to or higher than 2; secondly, the thickness of low permeability zone was accounted for more than 30% of the total; thirdly, the interlayer distributes stably and its thickness was equal to or higher than one meter; fourthly, separated layer injections of polymer should be conducted at the time when the polymer injecting volume was lower than 200 mg/L·PV. The effects of separated layer injections on the ultimate recovery of polymer flooding with different interlayer permeability ratios and different polymer injection amounts were shown in Fig. 4.

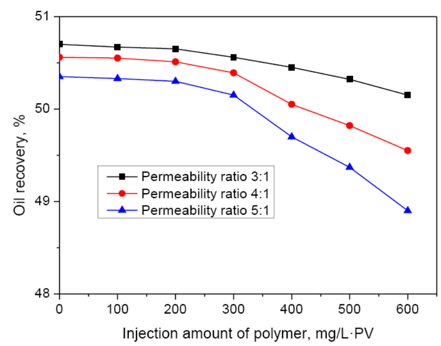

Figure 4—Recovery of polymer flooding at different interlayer permeability ratios and injection amount of polymer

Profile modification prior to polymer flooding As polymer flooding was implemented in mature and waterflooded reservoirs, especially in reservoirs with high permeability contrast and presence of thief zones. Preferential flow path occurred in these cases, and the polymer discharged in the production well quite early and rapidly[10]. In order to solve these problems and improve the performance of polymer flooding and polymer utilization rate, the profile modification prior to polymer flooding was studied and tested. The profile control and fluid channeling inhibition technologies were developed[11]. Different kinds of profile control agents were developed, such as high viscoelastic gel, weak cross-linked polymer gel and swelling particles. The evaluation method of profile control agents was also established. The application condition, injection time and injection amount of different kinds of profile control agents were tested. With the pre-profile control technology, the channeling phenomenon of displaced fluid was inhibited. The reservoir producing ratio was increased. The sweep volume and recovery factor of polymer flooding were improved.

Eccentric-wear prevention technology for production system Through the study of viscoelasticity fluid in tubing and sucker rod, the relationship between normal force of viscoelastic fluid of different concentrations and eccentricity of sucker rod was evaluated. The variation patterns of flow resistance for viscoelastic fluid through wellhole, pump valve and pump cylinder were determined. The eccentric wear phenomenon in tubing and sucker rod was mainly caused by normal force of viscoelastic fluid. On that basis, the stress testing technology of sucker rod was developed. Technologies including large passageway pump with low friction, full well centering, unified bar diameter, regular rotary sucker rod were formed.

These technologies were applied on 8,341 wells. The eccentric wearing portion was decreased by 78.4% after 1,356 days run [12].

Produced liquid handling technology The novel water and oil separating agent was developed to treat produced liquid containing polymers. The treatment efficiency was improved. The improved produced water treating process through sedimentation and filtrating was applied to decrease the water and oil separating time. The passing rate of three main indexes of water quality was improved.

Dynamic monitoring technology In the aspect of profile testing, the tracer well testing technique was developed and the neutron oxidation impulsion and electromagnetic flow well testing method was perfected and widely applied. They can maintain the demand in general injection profile testing. Moreover, a good performance was also achieved in the stratification testing. In production profile testing aspect, the well testing technique based on the relationship between flow and conductivity and down-hole fluid sampling technique was developed. Based on these technologies, the field tests results of polymer flooding can be monitored dynamically.

Performance prediction and economic evaluation technology The polymer flooding numerical simulation software was developed. Through reservoir simulations, field monitoring and analysis of polymer flooding, different optimization and adjusting measures were conducted in different periods of polymer flooding process to guarantee the field tests performance. The performance of polymer flooding was evaluated through the analysis of technology and economy. The drawbacks were found and the experiences were summarized. The input and output data was optimized to increase the overall economic profits of polymer flooding in the oilfields.

Generally, polymer flooding technology has taken the leading position in EOR techniques in China. As shown in field application, polymer flooding is able to be applied in continental sedimentation and heterogeneous reservoirs in China. Polymer flooding technique has been widely used in sandstone reservoirs with 13% (OOIP) incremental oil recovery factors over water flooding in average. Moreover, polymer flooding has been expanded and applied in conglomerate reservoirs and fault block reservoirs with the development of technologies. Since 2002, the oil production of polymer flooding has been increased to over 10 million tons each year (Fig. 5). During the 12th Five-Year Plan period, the oil production in Daqing Oilfield was up to 40 million tons per year. The EOR production of chemical flooding was around 13 million tons each year in which polymer flooding plays an important role to maintain the oil production in China. Polymer flooding in China owns the largest application scale and the best enhanced oil recovery performance in worldwide [13].

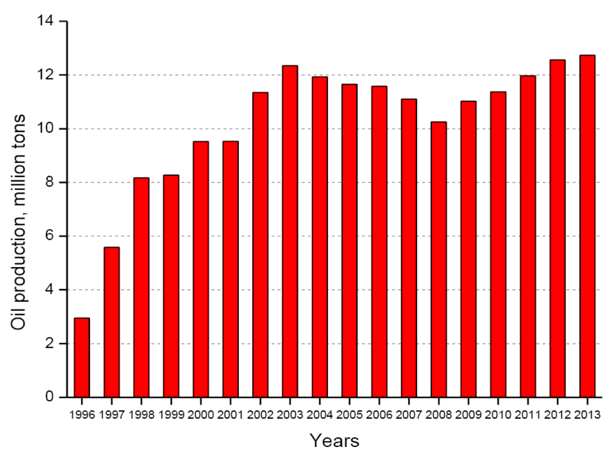

Figure 5—Annual oil production of polymer flooding in China

The remaining challenges and development trend of polymer flooding

With the extended application of polymer flooding to different types of reservoirs, new problems need to be solved. The main challenges of polymer flooding are listed below.

The development of temperature resistance and salt tolerant polymers At present, polymer flooding is mostly applied in low temperature and low salinity reservoirs. The target reservoir temperature should be below 80 °C with less than 10,000 mg/L salinity and 100 mg/L divalent cation concentration, because the traditional high molecular polymer has high viscosity in such conditions. When high molecular polymers (HPAM) are exposed to extreme conditions (reservoir temperature higher than 80 °C and the salinity greater than 20, 000mg/L), polymers might be degraded or polymer molecular chains could be crimped, thereby resulting in reduction of viscosity. Recently, some novel temperature/salt-resistant polymers were developed such as branching polymer GLP, star-shaped polymer STARPAM and associating polymer APP[14]. The relationship between viscosity and polymers concentration at temperature (90 °C) and salinity (35,000 mg/L) was shown below (Fig. 6). Polymers APP, GLP and STARPAM have higher viscosity compared with HPAM. These new polymer products are quite stable under 90 °C and 35,000 mg/L salinity conditions. However, they may lose their stability at a higher temperature or salinity reservoirs. For example, Tarim oilfield and Qinghai Oilfield in western China, reservoir temperature is 95–126 °C, salinity is 50,000–120,000 mg/L. Therefore, more stable polymer products need to be developed in future.

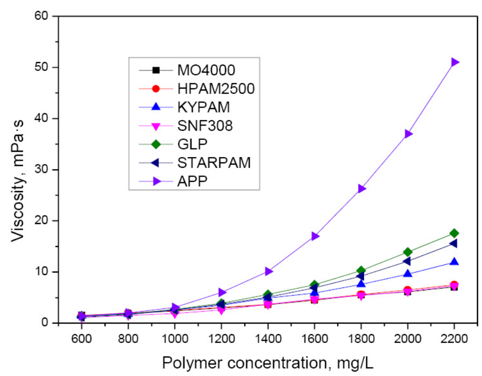

Figure 6—Viscosity of polymer solution with polymer concentration for different type polymers

The development of low molecular-high viscosity polymer products that suitable for low permeability reservoirs In low permeability reservoirs (permeability is less than 100 mD), high molecular polymer is difficult to pass through the pore throat due to the small pore throat size. There is an injection problem in this situation. Therefore, polymers with low molecular weight but higher viscosifying action need to be developed.

Field injection process equipment and supporting technology Firstly, the injection craft and facilities of polymer flooding need to be improved. For example, the preparation craft and injection allocation process should be improved to increase the adaptability and efficiency of some hardly dissolved polymers thereby reducing the cost. Secondly, the tracking adjustment technologies in field tests should be optimized as well. The single well adjustment process should be monitored over time according to the dynamic and static data of production and injection wells.

The Development and Present Situation of Chemical Combination Flooding Technique

The development process of chemical combination flooding

The development process of chemical combination flooding can be divided into three stages. The first stage was the indoor research stage which was initiated in 1980s. Referring to the research trends in America, the focused technique was micelle-polymer flooding technique. However, it requires a very high concentration of surfactant (generally large than 3 wt%) to form a microemulsion system. A high surfactant concentration leads to a high cost which might restrict its further field application. Afterwards, the study turned its direction to the alkali-polymer flooding technology. The alkali (sodium hydroxide) can react with acidic constituent in crude oil thereby producing surfactants in situ. Yields of surfactants could decrease the interfacial tension (IFT) between oil and brine. This research targets in high acidity oil reservoir. However, there are still two limitations remained in this technology. Firstly, the reducing level of IFT between oil and brine was poor. Secondly, the high concentration of alkali in polymer solution could significantly reduce the viscosity of alkali-polymer flooding. The enhanced oil recovery degree of indoor research was not high enough. Then the research turns its direction to the alkali-surfactant-polymer (ASP) combination system. The IFT could be significantly reduced (reach the ultralow level)[15], based on the synergetic effect between alkali and surfactant. The concentration of surfactant was normally about 0.2 wt% to 0.4 wt%. The concentration of alkali was around 0.4 wt% to 1.2 wt%. The alkali used could be NaOH, Na2CO3, NaHCO3, etc. Meanwhile, the presence of polymers can increase the viscosity of the solution. The ASP flooding showed better EOR performance than any other chemical flooding technologies (Table 5).

Table 5—EOR potential of chemical flooding techniques

EOR techniques	EOR (%)
Alkali flooding	2–5
Polymer flooding(HPAM or biological polymer)	7–14
Alkali-Polymer combination flooding	9–16
Surfactant flooding	5–11
Alkali-Surfactant-Polymer combination flooding	15–27
Foam combination flooding	10–25

In the second stage (1990s), chemical combination flooding pilot tests were conducted. Small well spacing ASP flooding pilot tests were conducted in Gudong, Shengli Oilfield in 1993. After 54% recoverable oil recovered by water flooding, the ASP flooding could increase oil recovery by 13.4% (OOIP). Thus, the total oil recovery could reach 67%. Since 1994, the chemical combination flooding was carried out in Daqing Oilfield in the western part of the middle area and Xing-5 area. Furthermore, the ASP flooding could enhance oil recovery by more than 20% (OOIP) after water flooding, by using surfactants (ORS, B100) imported from the USA [16].

Chemical flooding technology entered into the third stage (from 2000s) in the new century. The extended chemical combination flooding and industrial application tests were conducted. Due to the favorable performance of pilot tests, the industrialized chemical combination flooding was started from 2001 by using homemade high performance surfactants. In China, low surfactant concentration system was applied in ASP flooding. The IFT between ASP fluid (with surfactant HABS) and Daqing crude oil was shown in Fig. 7[15]. The concentration of polymer HPAM was 1500 mg/L. The result indicates that the ultralow IFT could be achieved by using 0.05wt%-0.3wt% of surfactants and 0.5wt%-1.2wt% of NaOH. The dosage of surfactant in ASP system could be reduced by adding alkali because alkali might increase the electronegativity and decrease the adsorption of surfactants on the rock surface. Indoor core flooding results indicate that ASP system could increase the oil recovery by 22%-25% after water flooding[2,15]. The surfactant concentration for pilot test was about 0.2 wt%-0.3 wt%. The ASP slug volume was about 0.4–0.6PV. Low concentration surfactant could reduce cost of the oil displacement system. The supporting technology in field tests was considered to be improved. These technologies include preparation and injection technology of ASP flooding, scaling inhibition and lifting technology and produced liquid treatment technology, etc. Therefore, ASP chemical combinational flooding has become an efficient EOR technology in China.

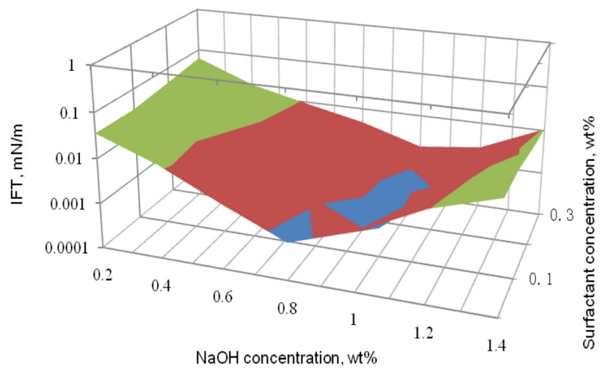

Figure 7—IFT between Daqing crude oil and ASP fluids with surfactant HABS

Current situation of chemical combination flooding field tests and applications

Five ASP flooding pilot tests were conducted in different areas of Daqing Oilfield since 1994. The incremental oil recovery factors were around 19%-25% (OOIP) after water flooding. Weak alkali ASP flooding was also conducted in the conglomerate reservoir located in the north part of the two center zones of Karamay Oilfield. The enhanced oil recovery was as high as 24.5% (OOIP) (shown in Table 6).

Table 6—Summary sheet of ASP flooding pilot tests in PetroChina

Project	Lithology	Injector/ producer	Well spacing (m)	Sandstone thickness (m)	Effective permeability (mD)	Chemical formulation	EOR (%)
Daqing Middle-West	Sandstone	4/9	106	10.5	509	Na_2CO_3+B100+HPAM	21.4
Daqing Xing-5	Sandstone	1/4	141	8.4	589	NaOH+ORS41+HPAM	25.0
Daqing North-Middle	Sandstone	3/4	75	13.1	567	NaOH+ORS41+HPAM	23.24
Daqing Xing-2 West	Sandstone	4/9	200	7.0	658	NaOH+ORS41+HPAM	19.40
Daqing North-1 West	Sandstone	6/12	250	12.9	512	NaOH+ORS41+HPAM	20.63
Karamay Middle-2 North	Conglomerate	4/9	50	15–22	674	Na_2CO_3+KPS+HPAM	24.5

On the basis of ASP flooding pilot tests, five extended ASP industrial tests (shown in Table 7) were carried out in Daqing Oilfield, using homemade surfactant HABS. From the perspective of reservoir types, the application area of ASP flooding has extended from high permeability reservoirs to intermedium permeability reservoirs. In order to inhibit the negative effect of strong alkali (sodium hydroxide) and test the performance of weak alkali (sodium carbonate) ASP flooding, the weak alkali ASP flooding extended field tests (as shown in Table 7) were conducted in Daqing Oilfield by using homemade petroleum sulfonate surfactant DPS. Fig. 8 showed the results of production curves of three ASP flooding industrial tests using HABS as surfactant in Daqing Oilfield.

Table 7—Industrial tests of ASP flooding in Daqing Oilfield

Project	Well numbers (injector/producer)	Well spacing (m)	Sandstone thickness (m)	Effective permeability (mD)	Chemical formulation	EOR (%)
Daqing Xing-2	17 /27	250	10.6	850	NaOH+HABS+HPAM	18.6
Daqing South-5	29 /39	175	13.3	867	NaOH+HABS+HPAM	19.8
Daqing North-1	49 /63	125	10.6	670	NaOH+HABS+HPAM	26.5
Daqing La North-East	45 /62	120	9.4	725	NaOH+HABS+HPAM	20.1
Daqing North-2 West	35 /44	125	8.1	533	Na_2CO_3+DPS+HPAM	21.6

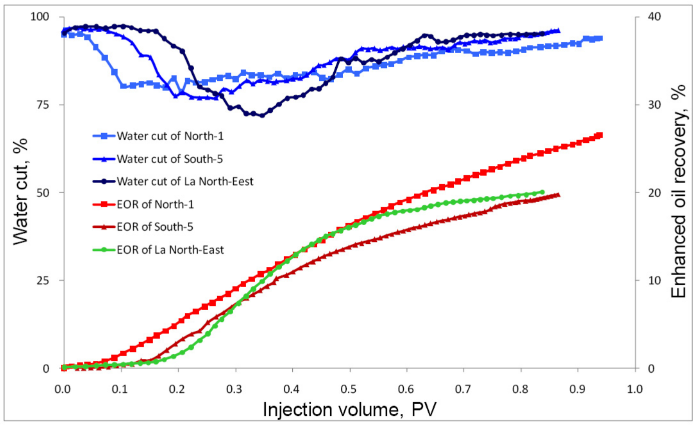

Figure 8—The production curves of three ASP flooding industrial tests

Industrial tests of ASP flooding showed a significantly high oil recovery. ASP flooding has entered into the stage of industrialized application up to now. The tests have proved that chemical combination flooding was an effective EOR technology for water flooded mature reservoirs in China. Based on good EOR performance of chemical combination flooding field tests, Daqing Oilfield opened up four blocks to conduct industrialized application of ASP flooding. They are East-2 zone of Xing-1–2, South-6 zone, East-1 zone of Xing-6 and East-2 zone of Xing-6. The total producing geological reserves are 28.61×10^6 m^3 (Table 8). Chemical combinational flooding has been selected as the main alternative EOR methods after the 12th Five-Year Plan. It will become an important strategy to guarantee the oil production with 40 million tons per year in Daqing Oilfield.

Table 8—ASP flooding commercial application blocks in Daqing Oilfield

Blocks	Well numbers (injector/producer)	Well spacing(m)	Sandstone thickness (m)	Effective thickness (m)	Effective permeability (mD)	Geological reserve ($\times 10^6$ m^3)
Daqing South-6	144 /160	175	13.2	10.7	539	12.736
Daqing Xing-1–2	112 /143	150	10.4	8.6	517	6.665
Daqing Xing-6 I	102 /129	141	6.8	5.7	550	4.690
Daqing Xing-6 II	105 /109	141	7.3	5.7	515	4.523

The integrated techniques of chemical combination flooding

Chemical combinational flooding technique was improved continuously. A series of technologies have been developed for industrialization application of ASP, involving ASP formulation evaluation and optimization, scenario design and numerical simulation, injection allocation technology, lifting technology, dynamic monitoring and tracking[16–17].

ASP formula evaluation and optimization The surfactant quality and combinational system evaluation standard has been established. Every testing index and evaluation methodology have been established[18]. Formula was chosen based on the target reservoir conditions. The surfactant and polymer products quality for field tests and application should be under strict control.

Scenario design and numerical simulation Each combinational flooding test and application will pass a series of processes, including geological analysis, reservoir description, series of strata combination, well pattern and space optimization and injection parameter optimization. SIM-EOR simulation software has been developed and applied to optimize the scheme and parameters.

Injection allocation technology The proper injection parameter design and ground engineering optimization design are important to guarantee the favorable performance of field tests. To ensure the injection efficiency and reduce the cost of chemical combination system, reasonable injection scheme and craft were employed (such as drip distribution injection craft, single agent single pump, high pressure with three agents and low pressure with two agents combined injection technique) [19].

Lifting technology To overcome scaling problem in ASP flooding, ceramic screw pump and small interference screw pump was used to enhance performance of anti-scale. Moreover, scale inhibitor was also added to prevent scaling. The oil lifting system could run smoothly with these technologies.

Chemicals monitoring of produced liquid handing In order to understand scaling law in oil well, the relationship between scaling degree and ions concentration (Si^{4+}, $CO3^{2-}$, Ca^{2+} and Mg^{2+}) was studied. Scaling prediction method was set up based on ions concentration change rule in produced water (Fig. 9) [20]. Scale prevention measures were conducted by either chemical and/or physical methods based on different scaling degrees. Oil/water separating system could ensure the treatment of ASP produced fluid meet the requirements of oil and reinjection water[2].

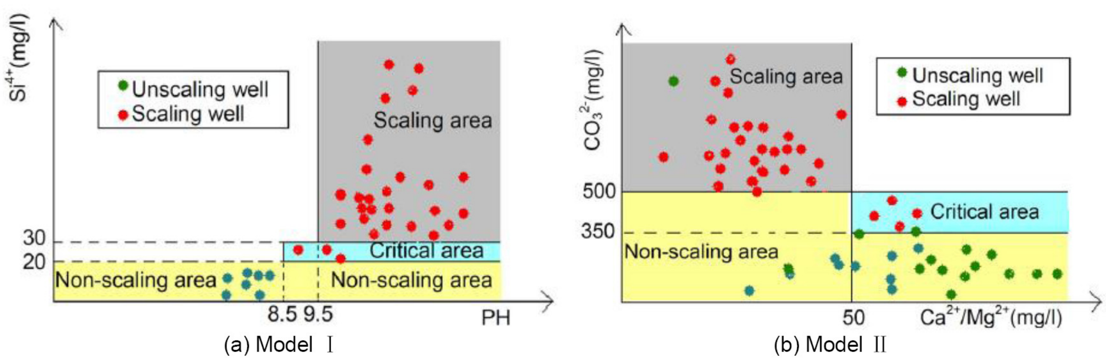

Figure 9—Scaling prediction model of ASP flooding in Daqing Oilfield (a)Model I (silicate scale); (b)Model II (carbonate scale)

Dynamic monitoring and tracking Main dynamic oil production data such as oil production, liquid production capacity, water cut and oil recovery were tracked. Adjustment measure was employed in time to guarantee good performance of field tests.

The remaining challenges and development trend of chemical combination flooding

There are two main limitations remained in ASP flooding field tests. Firstly, the strong alkali might cause scaling and erosion which shortened the pump checking cycle and increased the maintenance work. Such phenomenon frequently occurred when high concentration alkali existed in production liquid. Though physical and chemical scaling inhibition measures could extend the average pump-checking interval from 90 days to 160 days, the average pump-checking cycle for ASP flooding was only half of that of polymer flooding[2].

Secondly, the emulsified level of produced liquid was very high. The treatment process was difficult and the cost was high. In South-5 and North-1 East ASP flooding industrial tests, water and oil were hardly separated being strong emulsification. The electric field of electric dewatering unit was unstable, leading to both water contents in exported oil and suspended solids content in water exceed the standard specifications. This situation was even worse with the presence of high concentrations of alkali and surfactant in the produced fluid[2]. Demulsification and dehydration of produced liquid could be resolved by a series of measures, including modification of electrodes of electric dewatering unit, and higher dosage of demulsifier and defoamer. However, the costs of these techniques were relatively high.

In order to avoid the negative effect of alkali and improve and optimize the technology of chemical combinational flooding, alkali-free surfactant-polymer (SP) flooding has become a hot issue at present. SP flooding pilot tests have been arranged in Liaohe, Jilin, Xinjiang Oilfield, etc. These reservoirs are sandstone reservoirs with different permeability, fault block and conglomerate reservoirs. SP flooding started to be applied in Jilin Oilfield from 2009. Pilot tests of SP flooding have also been conducted in Liaohe and Karamay Oilfield in 2010 and 2011, respectively. SP flooding pilot tests have been conducted in Changqing and Dagang Oilfield in 2011 and 2012, respectively (Table 8) [21].

Table 8—SP flooding pilot field tests in PetroChina

Projects	Well numbers (injector/producer)	Well space (m)	Permeability (mD)	Reservoir temperature (°C)	Salinity (mg/L)	Slug volume (PV)	Estimated EOR (%)
Jilin Honggang	16/16	142	163	55	14000	0.66	14.8
Liaohe Jin-16	23/33	210	2859	55	3500	0.51	15.4
Karamay 7-Central	18/26	150	119	40	7990	0.56	15.5
Daqing		175	500–900	45	4100	0.49	15.0
Changqing Maling	16/25	150	67	51	12610–26130	0.65	15.1
Dagang Gangxi-3	11/36	300	675	53	13450	0.60	13.0

The overall tendencies of chemical combination flooding in China are known as: the chemical combination flooding system has been developed from strong alkali ASP flooding to weak alkali ASP, then to alkali free SP flooding. The target reservoirs have been exploited with various conditions, from high permeability to low permeability; from low salinity reservoirs to high salinity reservoirs; from low temperature reservoirs to high temperature reservoirs.

There are three major future concerns of chemical combination flooding, which are listed below:

The development of oil displacement surfactants with high efficiency and low cost To improve the performance of SP flooding, higher quality surfactant for oil displacing purpose is needed. Recently, some novel surfactants have been developed, including new amphoteric surfactants, anionic-nonionic surfactants, and double chains surfactants. Those surfactants could reduce the IFT between oil and formation water to ultralow level. Additionally, some of them showed a better salt/divalent cation resistant ability[22]. However, the cost of those surfactants for manufacture was high. Therefore, the development of high efficient surfactants with cheap price remains to be strengthened.

Improvement of produced liquid treatment processes to reduce costs further Because of high emulsification of produced liquid in ASP flooding, the high performance demulsifier and purifier are essential to be developed. The produced liquid treatment craft should be improved to reduce the cost. New demulsifiers and oil/water separation agents for ASP flooding production liquid handing were developed. Some new chemical and physical treatment methods were also presented [23–24].

Improvement of field injection process and tracking adjustment technology According to the actual conditions, the injection processes and parameters should be optimized. Also, the tracking and adjustment technology should be improved. Major indicators (oil production, liquid producing capacity, water cut, oil recovery) of production wells need to be followed in time, thereby ensuring the performance of field tests.

The Development and Present Situation of Foam Flooding Technique

Present status of foam flooding pilot tests

Foam flooding is an oil displacing technology by using foam fluids. Foam fluids can be formed by incorporating gas and surfactant solution into the pay zone. As the foam fluid has high resistance factor, foams can block the water channeling zone to increase the sweep volume. Meanwhile, the foaming agent has ability to decrease the IFT between oil and water, leading to the increment of the oil displacing efficiency. Therefore, foam flooding is effective in improving oil recovery. Foam flooding technology has been studied and tested for about 30 years in China. Some good experiences have been achieved in pilot tests. However, there are still some deficiencies need to be improved.

From 1994 to 2012, twenty foam flooding pilot tests have been carried out across China (Table 9)[3, 25–29]. Among the twenty tests, ten was nitrogen foam flooding (five from 1994 to 1999 and five from 2003 to 2007), two was natural gas foam flooding (one in 1997 and one in 2009), and eight was air foam flooding (one in 1996 and seven from 2005 to 2012). Air foam flooding plays a more important role in foam flooding in recent years because of its low cost. From the perspective of foam flooding scale, the pilot tests are in small scale in early stage. The number of projects with more than 10 production wells and longer (more than half a year) operation time was only seven. Most of them were trial tests. From the perspective of foam flooding performance, the 20 pilot tests can be divided into two categories. The first category was 17 projects with favorable performance, these projects have a larger increased oil production or the effectiveness portion of wells was large than 50%. Of the 17 projects, ten were conducted in high permeability reservoirs, four were in low permeability reservoirs, and three were in viscous oil reservoirs. The second category contains three projects which with low increased oil production or low effectiveness portion of wells. Two projects had severe gas fingering problems.

Table 9—Summary of Foam flooding pilot tests in China

Time	Oilfields	Gas type	Permeability (mD)	Well numbers	Injected foamer or foam solution	Increased oil production (tons)	Effective rate of wells (%)
1994	Shengli	N_2	1300	8	9.7 tons foamer	≥6,000	50
1995	Shengli	N_2	1300	8	18 tons foamer	≥5,000	
1996	Baise	Air	13.41–450	7	34,300 m^3 solution	≥14,800	75
1996	Liaohe	N_2	1,065	7	691.45 tons foamer	≥10,800	
1996	Baise	N_2	24–150	7	2,266 m^3 solution	883	57
1997	Daqing	Natural gas	314	10	0.552 PV ASP foam	≥78,501	70
1999	Liaohe	N_2	1,065	48	5,373.6 tons foamer	174,100	
2003	Shengli	N_2	1,500	4	34.75 tons foamer	≥12,072	100
2003	Shengli	N_2	1,300¯x2013;1,800	12	274.3 tons foamer	11,000	50
2004	Baise	N_2	24–150	4	600 m^3 solution	509.6	75
2005	Yanchang	N_2	140–900	9	4,477 m^3 solution	3,486	66
2005	Changqing	Air	0.3–0.5	11	1,128 m3 solution	5,157	54.5
2006	Changqing	Air	30	6	3,606 m^3 solution	≥118	33.3
2006	Changqing	Air	30	6	2,022 m^3 solution	≥440	83
2007	Zhongyuan	Air	235.5	20	13,801 m^3 solution	2450	
2007	Yanchang	Air	0.82	16	1,091.8 m^3 solution	573.5	100 (#54 group) 62.5 (#55 group)
2007	Daqing	N_2	600–1,000	12	11,000 m^3 solution		Gas fingering
2009	Daqing	Natural gas	520–1,000	18	0.6PV solution		Gas fingering
2009	Changqing	Air	3.47	17	0.25 PV foam solution	EOR=7.19% (predicted)	71
2012	Dagang	Air	1,016	18	0.35 PV foam solution	84,800 (predicted)	

At present, the development tendency of foam flooding technology is shifted from nitrogen foam flooding, natural gas foam flooding to air foam flooding. Based on pilot tests, foam flooding is widely applied on oil reservoirs with various conditions (from high permeability to low permeability, low temperature and low salinity to high temperature and high salinity).

The remaining challenges and development trend of foam flooding

The main challenges of foam flooding are listed below:

The foam formula should be optimized The foam generated by foam formula with a poor stability could be easily broken up in porous media. This might cause a gas breakthrough phenomenon. For example, the gas fingering problem has been found in Daqing Lamadian Oilfield (foam combination flooding after polymer flooding). The wells were closed and the project scheduled task had to be altered. Besides the severe reservoir heterogeneity, the possible reason of gas fingering was the poorer stability of foam formula used in foam flooding. The low interfacial tension binary foam combination formula system (0.3% surfactant + 1000 mg/L polymer) was tested. The foaming ability and foam stability were poor and the profile control ability was weak under the reservoir condition [25]. Thus, the foaming formula system should have strong foaming ability, high stability, low adsorption ability and oil tolerance ability. Some novel modified foam formula has been developed and attracted more attention in recent years, involving polymer enhanced foam, gel enhanced foam and nanoparticle enhanced foam. Of them, nanoparticle enhanced foam showed a significantly higher stability. For example, nanoparticle can improve the foam stability by more than one order of magnitude[30-31].

The foam injection mode and parameters should be optimized The gas/liquid ratio, injecting velocity and injecting time should be confirmed according to the target reservoir conditions. Both co-injection of liquid/gas and foam injection could be used instead of water alternating gas flooding to gain better performance. For example, the gas finger problem occurred in Daqing North 2–6–33 well group because of the unreasonable gas/liquid ratio which made gas more easily to breakthrough when gas alternating liquid injection mode was adopted. Gas/liquid ratio of nitrogen foam flooding in North 2–6–33 well group was about 2:1 on the ground. Based on the pressure drop during the injection process, the gas/liquid ratio in pay zone could be 3:1. Because of the weak stability of foam and high gas injection rate (90–140 m3/d), the gas dissociate phenomenon occurred before foam flooding process. This phenomenon finally made gas break through[25]. The reasonable gas/liquid ratio on the surficial condition and under subsurface condition was from 0.5:1 to 1:1 and from 1:1 to 2:1, respectively, based on a successful field experiences[3]. Thus, the optimized injection parameters also play an important role for good foam flooding performance except foam formula.

The target reservoir condition should be confirmed carefully and the oxygen should be monitored to guarantee the safety during air foam flooding Based on low temperature air oxidation reaction mechanism, the recommended temperature of the target zone for air foam flooding is above 70 °C. However, from the experience of pilot tests of air foam flooding, the real pay zone temperature is a little bit lower than the recommended temperature[3]. Air oxidation reaction needs more time to be carried out at low temperature condition. If the reaction period could be further extended, the oxygen in produced gas would be remained in a safe level. To better understand the underground air flow, the casing pipe pressure in the production well should be monitored during air foam flooding process. The pay zone pressure and oxygen concentration in produced gas should be monitored and analyzed regularly for safe concerns.

Conclusions

1. Polymer flooding has been applied in more than 50 blocks in Daqing Oilfield. The average incremental oil recovery factors in representative blocks was around 13% (OOIP) over water flooding. Generally, one ton of polymer could increase oil by 118.7 tons. Ten supporting technologies (polymer screening and evaluation, project design and numerical simulation, well completion technology under low shearing rate, high performance preparation and injection equipment and craft, separated layer injection technology, profile control technology before polymer flooding, eccentrically-wearing inhibiting technology for production system, produced liquid handling technology, dynamic monitoring technology, performance prediction and economic evaluation technology) were developed based on field experience which guaranteed the application performance of polymer flooding. At present, polymer flooding is extended to be applied in complex fault block reservoirs and conglomerate reservoirs. Polymer flooding plays an important role in enhanced oil recovery in China.
   The main technical challenges of polymer flooding in expanded applications are: the development of heat/salt resistant polymers (temperature is higher than 95 °C, salinity is more than 35,000 mg/L), high viscosifying action but low molecular weight polymers for low permeability reservoirs.
2. Chemical combination flooding was significantly improved in recent years. ASP flooding could remarkably increase oil recovery. 19%-25% (OOIP) incremental oil recovery factors were obtained for high water cut oilfield in Daqing and Xinjiang oilfields based on field tests. The tests indicated that chemical combination flooding is an effective alternative EOR method after polymer flooding. Now it has entered into stage of industrialized application. A complete set of supporting technologies (ASP formula evaluation and optimization, scenario design and numerical simulation, injection allocation technology, lifting technology, chemicals monitoring of produced liquid handing, and dynamic monitoring and tracking) were developed in field tests which guaranteed the performance of ASP flooding. The overall development tendency of chemical combination

flooding is shifted from strong alkali ASP to weak alkali ASP, and then to alkali free SP chemical formula system. The target reservoir is extended from equipped sandstone reservoirs to conglomerate reservoirs, and then to complex fault block reservoirs.

The remaining challenges of chemical combination flooding are: scaling and short pump-checking periods caused by alkali, the difficulty and high cost to treat produced fluid. So the produced liquid treatment processes should be improved to reduce costs. The oil displacement surfactants that have high efficient but low cost should be developed in new combination system.

3. Twenty foam flooding pilot tests have been carried out across China from 1994 to 2012. These include nitrogen foam flooding, natural gas foam flooding and air foam flooding. Most of these tests have gained good oil recovery performances. The application reservoir condition for foam flooding is also extended.

   The main challenge of foam flooding is gas breakthrough. So the foam formula needs to be optimized, including foaming ability, stability of foam, low adsorption ability and oil tolerance ability. The foam injection mode and parameters should also be improved in future.

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