Chapter

Development and Application of Chemical EOR Technologies in China Offshore Oil Fields

Jian Zhang, Fengjiu Zhang, Xiaodong Kang and Baozhen Li

Abstract

At present, polymer flooding as the most effective chemical EOR technique is widely used in onshore oil fields in the world. Also, it has been successfully applied in China offshore oil fields as a major EOR technology. CNOOC has preliminarily established a chemical flooding (polymer, polymer-surfactant, weak gel, etc.) technology system including high-efficiency chemical flooding agents, platform injection facilities, and produced liquid treatment technology. Since 2003, pilot tests and field applications were carried out in S, L, and JW oil fields, and predicted oil increment and good economic benefits have been achieved, which proved that offshore chemical EOR technology is feasible and economical. It has explored a new road for increasing the recovery of offshore oil fields and provided a solid technical guarantee for their economic and efficient development.

Keywords: offshore oil field, chemical flooding, EOR, review

1. Introduction

By the end of December 2017, China's offshore oil production accounted for 22.3% of the national oil production [1–4]. The average offshore field water cut of oil fields was 86.6%, with relatively low oil recovery rate, only 21.1%. Bohai oil field is the largest offshore oil field in China. In 2010, its oil and gas output reached 30 million square meters, accounting for about 15% of the national total, which played an important role in stabilizing the energy supply in eastern China. Heavy oil accounts for 85% of the oil reserves in Bohai oil field, and the main development bottlenecks of these heavy oil fields are high crude oil viscosity, strong reservoir heterogeneity, and poor water drive efficiency. In particular, the viscosity of underground crude oil in some heavy oil reservoirs reaches 200–700 mPa s, and their recovery factor from traditional water flooding could only reach about 12% [5–9]. It could be seen that the research and application of enhanced oil recovery technology in offshore heavy oil reservoirs are of great significance for the stable production and economic efficient development of Bohai oil field.

2. The technical challenges of offshore chemical flooding

Chemical flooding has been successfully carried out in onshore oil fields in China for nearly 30 years. The implementation of traditional polymer flooding technology requires a large amount of freshwater supply, large injection allocation equipment, good reservoir conditions, and loose environmental requirements. It is difficult to meet these requirements in offshore oil fields. To realize the field application of polymer flooding technology, there are several challenges to overcome to conduct offshore chemical EOR projects:

1. Lack of fresh water on offshore platforms. It is almost impossible to use fresh water to prepare polymer for offshore polymer flooding. Only seawater (salinity 32,000–35,000 mg/L) or formation water could be considered.

2. Narrow space of offshore platform. The equipment for polymer solution preparing and injection is required to be compact, flexible, and more efficient. At the same time, the polymer is required to have excellent and efficient viscosity properties, including temperature and salt resistance and instant solubility characteristic.

3. The reservoir conditions are complex. For example, most Bohai oil fields have many high-permeability heterogeneous layers, high-salinity formation water, and high-viscosity crude oil.

4. Large well space. Most offshore oil fields were developed with large well space (350–600 m) and anti-nine-spot well pattern.

5. Environmental requirements for offshore oil field development are high. It is difficult for produced fluid from polymer flooding to meet standards in the last treatment on the platform, which will have a great impact on water reinjection.

6. There is a big difference between offshore oil field and onshore ones in development model and polymer injection timing, so it is necessary to establish evaluation methods and standard for offshore polymer flooding performance [5–9].

3. Research and development of offshore chemical EOR techniques

It could be seen that the research and application of enhanced oil recovery technology in offshore heavy oil reservoirs are of great significance for stale production and economic and efficient development of Bohai oil field. Based on about 20 years of research offshore chemical EOR techniques, a series of resolutions and techniques were developed including high-efficiency driving agents, platform polymer injection distribution technology, produced fluid treatment technology, and performance evaluation method for early-stage polymer flooding. These techniques had been carried out in S, L, and JW oil fields. The water cut was controlled at a low level, and the incremental oil was obviously enhanced.

3.1 Development and application of novel salt-resistant polymers

Bohai oil field has the characteristics of high crude oil viscosity, large well spacing, high water salinity, and limited platform space. Thus, the suitable polymer agent should have high-viscosity property, good salt tolerance, aging stability, and fast-dissolution ability. In order to expand polymer injection scale, two kinds of salt-resistant polymer were investigated and applied in Bohai Bay.

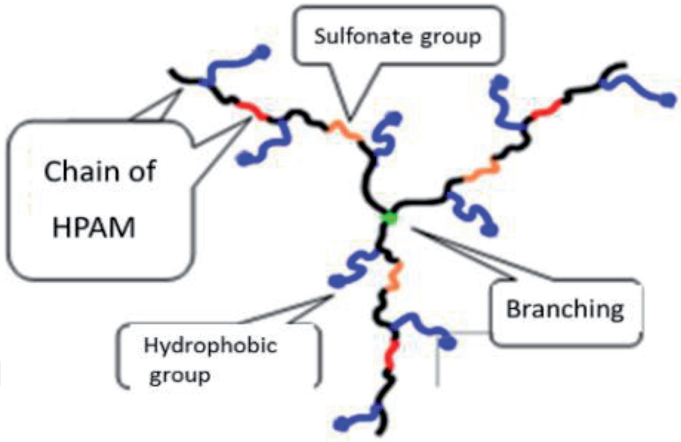

Figure 1.
Schematic of hydrophobic associated polymer.

3.1.1 Hydrophobic associated polymer

With reference to the research of hydrophobic acrylamide polymers and the literature on the synthesis of ultrahigh-molecular-weight hydrolyzed polyacrylamide, a new kind of polymer was designed with branched structure and hydrophobic associative units with micro-blocks (**Figure 1**). Meanwhile, a high-molecular-weight hydrophobic associative polymer industrial synthesis technology and polymer fast-dissolution technology was developed which could meet the requirements of large-scale application of high-efficiency offshore EOR technology [10, 11]. Under above conditions, the viscosity of hydrophobic associated polymer is 3–5 times that of ultrahigh-molecular-weight HPAM, the hard water resistance is increased by three times, the shear and aging retention rate are increased by 1.6 times, the residual resistance coefficient are increased by 2–3 times, and the dissolution time is shortened to 40 min.

Hydrophobic associated polymer has been applied in Bohai oil field since September 2003 and has achieved significant oil and precipitation effects [7–10].

3.1.2 Structural composite polymer

The performance of polymer depends on the molecular structure. Structural composite polymer is a kind of polymer with high sterically hindered side group on its skeleton, which exhibits relative rigidity in the solution, and the polymer molecule is strengthened under relatively harsh conditions by increasing the kinetic radius. Also a functional monomer which adjusts the amphiphilic nature of the polymer molecule is introduced into the molecular structure of the polymer to improve the solubility of the polymer. Structurally, polymer molecules contain diversified and multifunctional monomers, hence the name structural composite polymers (**Figure 2**). By adjusting the type and proportion of functional monomers, the salt and temperature resistance ability of polymers was improved. The polymer at lower concentrations could significantly reduce the viscosity of the heavy oil and significantly improves the fluidity of the heavy oil [12–14]. Above polymer had been injected in several pilot wells in Bohai oil field since December 2018.

3.2 Chemical flooding injection system on offshore platform

In order to promote the application of polymer flooding technology in offshore oil fields, it was necessary to combine the special conditions of offshore platforms to break through the bottleneck limitation of the huge polymer dispensing system

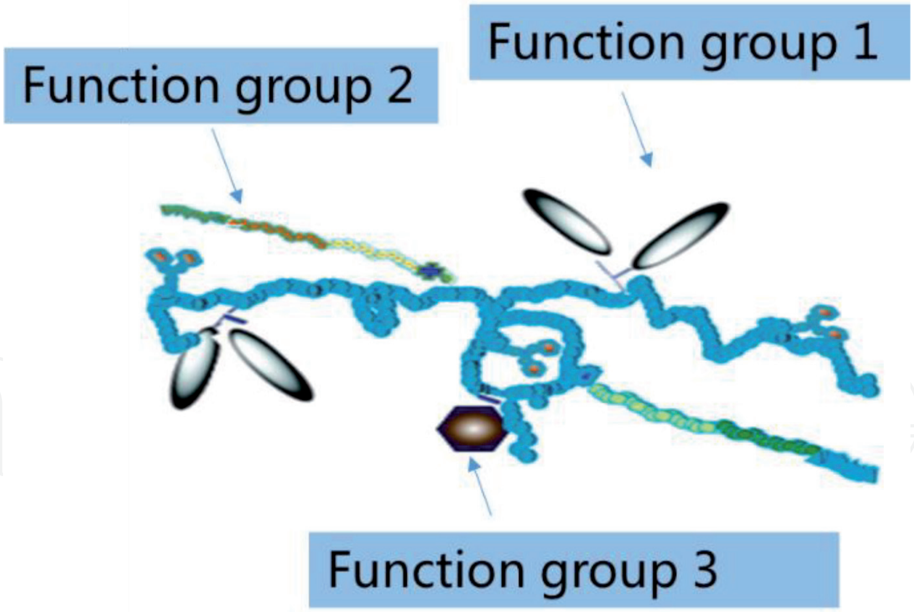

Figure 2.
Schematic of structural composite polymer.

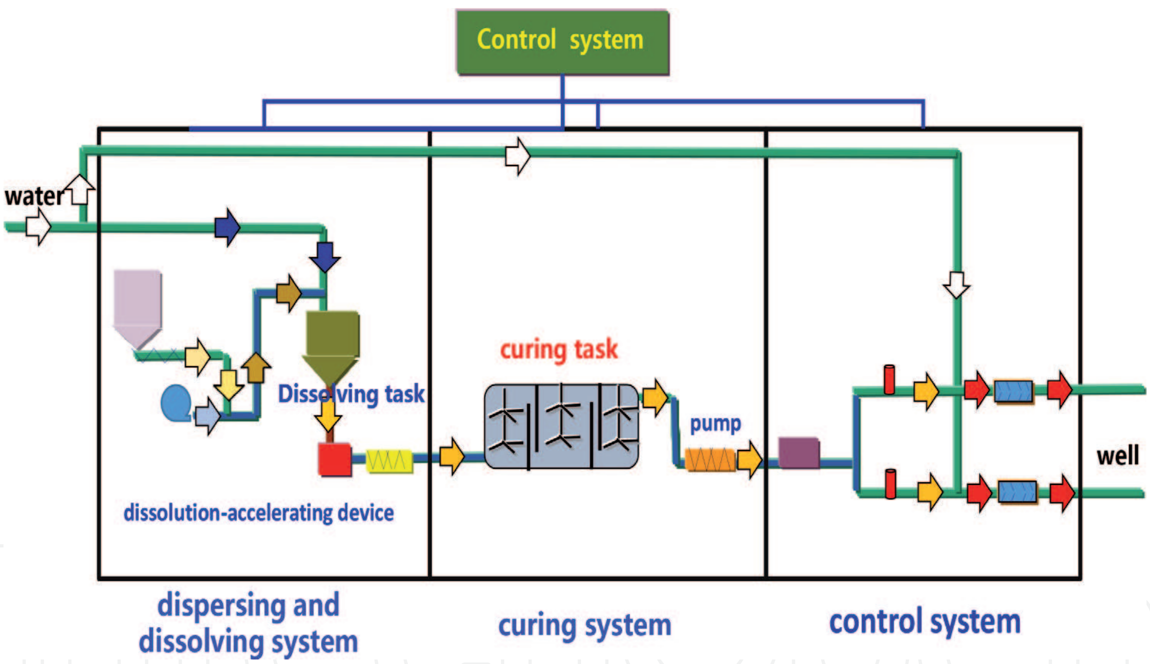

Figure 3.
The process of offshore platform injection system.

and achieve miniaturization, high efficiency, and modularization of the polymer injection system [15, 16]. The offshore polymer dispensing equipment included four systems: the dispersing and dissolving system, the curing system, the high-pressure injection system, and the control system (**Figure 3**). Each system was independent and convenient to install according to the site conditions.

Dispersing and dissolving system was the core of the rapid dissolving device. According to their viscoelastic characteristics, swelling polymer micelles were stretched during going through the gaps of the stator and rotor by using moderate stretching method. More water molecules permeate into the inside of the polymer micelle. At the same time, polymer molecules at the micelle's surface are stretching down into the water. Curing system achieved the full dissolution and ripening of the polymer solution. The size was dependent on the injection volume and curing time of the polymer solution. In order to ensure fully dissolution, the interior of the curing tank was optimized. The curing tank was separated into the inlet chamber, ripening chamber, and outlet chamber through a choke plate [15].

High-pressure injection system was applied to achieve the flow distribution and pressurization of the polymer mother liquor. The polymer mother liquor is distributed by a flow distributor for each well and then pressurized by a high-pressure injection pump.

Control system was applied to achieve automatic control of the entire polymer dispensing system, automatic data acquisition, and variable frequency control equipment for power equipment.

The online polymer dissolving technology was combined with technologies of polymer powder transmission by positive pressure gas, multistage polymer dispersion and stretching, graded maturation, and high efficient mixing, as the polymer dissolving time shortened to 40 min with high-viscosity retention rate (91%). Under same injection amount, area was saved by 21%, and weight was reduced by 37%. The improved facility has operated steadily in Bohai oil field for 2 and a half years.

3.3 Reservoir dynamic analysis method for offshore chemical flooding fields

The reservoir dynamic analysis method for polymer flooding in onshore oil fields is mature where the polymer injection is started when water cut is over 80%. However, in some offshore field, polymer injection was conducted at very low water cut (even <20% in some case) for the limited life of platform [6–8, 16]. The traditional polymer flooding evaluation method is not applicable in offshore early-stage polymer flooding projects for their short water flooding period, and the effectiveness of injection and the calculation method of incremental oil are not applicable. Based on the power law fluid's stable flow in pore media, considering non-Newtonian and multilayer heterogeneity of polymer solution, a Hall curve evaluation method of early polymer flooding is established. The principle is to use pressure and injection data to draw improved Hall curve of polymer flooding in linear form.

From **Figure 4**, it could be seen that, unlike the traditional Hall curve of polymer flooding, the slopes and intercepts of the improved Hall curve could be used to directly calculate the fluidity and resistance coefficients during polymer flooding, thus solving the reservoir dynamic analysis problem in early-stage polymer injection projects.

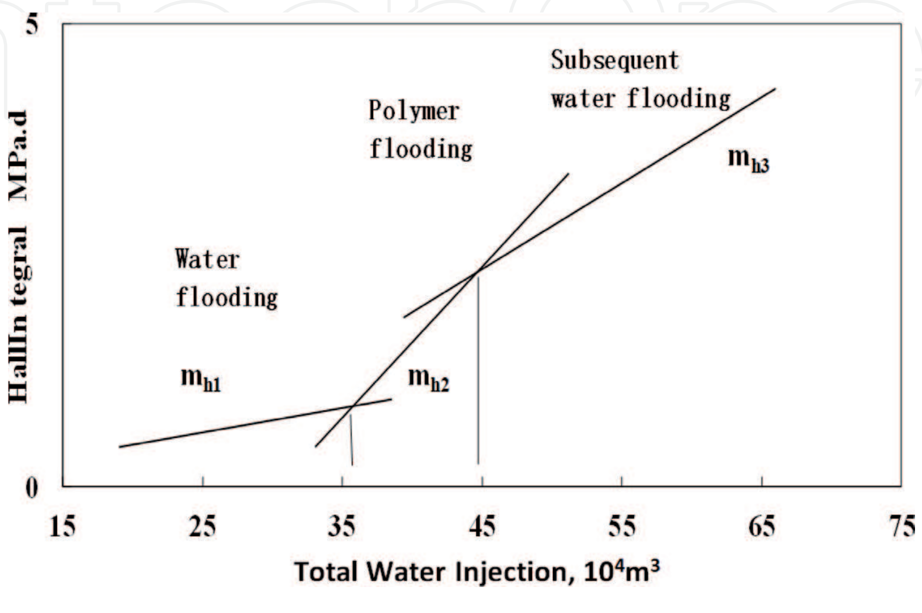

Figure 4.
Schematic diagram of calculation for resistance coefficient and residual resistance coefficient.

3.4 Treatment technology of chemical flooding produced fluid in offshore platform

Partially hydrolyzed polyacrylamides with high molecular weight (HPAM), after undergoing a series of chemical, mechanical, and thermal degradations, are back produced, making the oil-water interface highly electronegative and forming a strong electrical double layer. The repulsive force between oil droplets affects their aggregation and coalescence, and at the same time, the adsorbed polymers also increase the strength and viscoelasticity of the oil-water interface film. As a result, the emulsified oil droplets are of small particle size and strong stability. Therefore, the oil-water separation of produced fluid from polymer flooding is more difficult than that from water flooding. Hence, devices with much longer residence time and several times larger size are required for produced water treatment [17, 18].

However, platform space is limited for offshore oil fields; the abovementioned practice cannot be implemented. At present, the treatment process of polymer-containing produced fluid in Bohai oil fields is a so-called three-stage treatment process similar to that of water flooding. For example, the comprehensive water content of the produced fluid is 78% in Bohai A oil fields, and the average polymer concentration is 150 mg/L. The oil treatment system includes a one-stage three-phase separator, a two-stage thermal settling separator, and a conventional electric dehydrator (**Figure 5**). The wastewater treatment system mainly includes a tilted plate separator, a gas flotation unit (GFU), a walnut shell filter, and a residue conversion system. The abovementioned process represents the traditional process of produced fluid treatment for water flooding oil fields. For different polymer flooding oilfields, the original water flooding process have different complexity and methods for adaptive modification for polymer flooding projects.

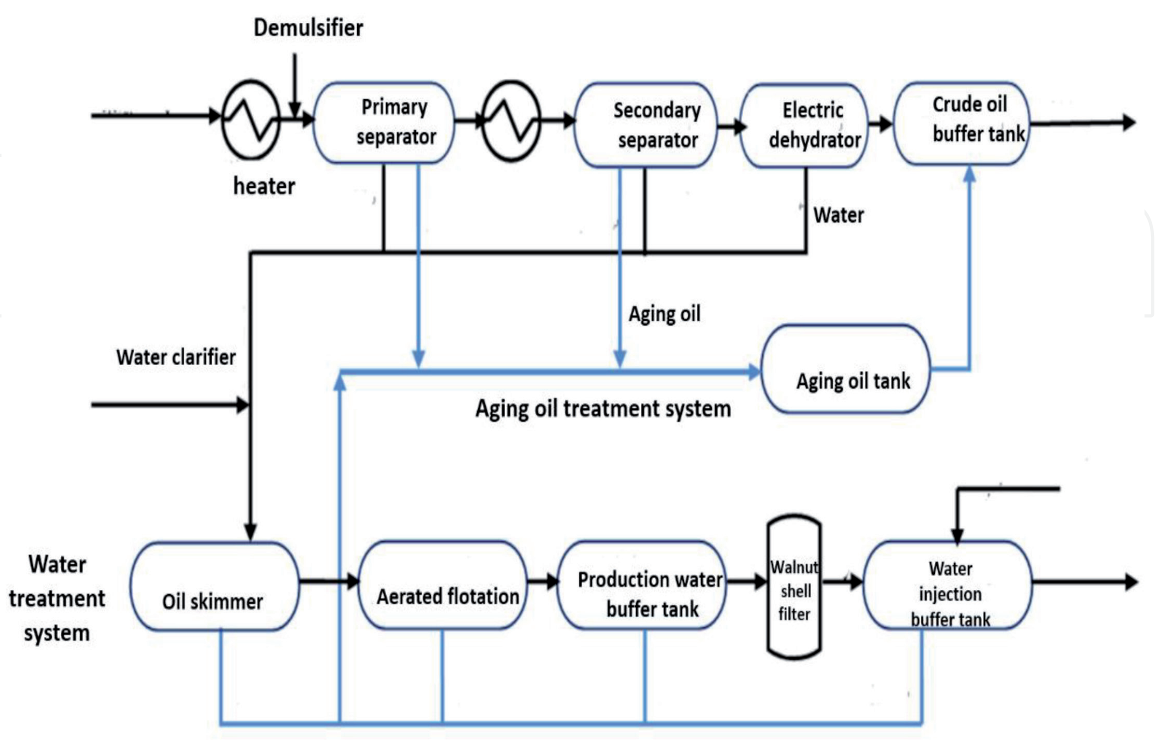

Figure 5.
Treatment process of produced fluid in Bohai A oil field.

4. Field application of offshore chemical EOR technology

In order to improve the development effect of offshore oil field during the effective period of platform, offshore chemical flooding was carried out in three Bohai oil fields since 2003 (**Table 1**), and good economic benefits have been achieved [6, 7, 19–25].

4.1 Polymer flooding in S field

S oil field is located at the coast of Liaodong, Bohai Bay, with stable distribution and good connectivity. Its reservoir rocks are feldspathic quartz sand composed mainly of fine sands. The crude oil in S oil field is highly viscous, varying from 13 to 380 mPa s, with an average of 70 mPa s at reservoir conditions. It was put into operation since 1993 with inversed 9-point well pattern. From the very beginning, the enhanced oil recovery technologies were taken into consideration, and polymer flooding showed great potential among these technologies. Since September 2003, the first single-well polymer injection pilot in China offshore field was successfully carried out in S field [19–21]. In October 2005, the well group polymer injection was carried out in AJ platform in S oil field, which consisted of four injectors and one central producer and seven peripheral producers. After 3 years of well group test, the expected incremental oil was obtained. Based on the well group polymer injection test result in S field, the expanded polymer injection project was implemented in mid-2008. Up to 2014, 24 wells were successively converted to polymer injectors, and significant incremental oil was achieved (**Figure 6**). By the end of 2017, 4.75 million cubic meters of cumulative oil were achieved, increasing recovery rate by 5.2%.

4.2 Chemical flooding in L field

L oil field is located in Bohai Bay, characterized by huge thickness, high permeability, severe heterogeneity, high crude oil density (0.947 g/cm^3), and medium oil viscosity (7.2–19.4 cp). L oil field was put into production in January of 2005 and started to inject water in September of 2005. Based on well understanding of the mechanism and effect of the early polymer flooding, single-well polymer

Indexes		S	L	JW	Daqing
Reservior Oil Viscosity (mPa. s)		70	16	17	8
		13.3-442.2	13.9-19.4	6.1-26.5	7--10
Well Pattern		Inversed 9 point pattern			5-spot pattern
Well Spacing (m)		350-590	350-400	400	106-200
Average Thickness (m)		32.4	45.2	19.3	11-21
Injected water (mg/L)	Salinity	9600	2873	3000	4600
	Divalent cations	810	260	34	20
Polymer Injection Time	Water Cut (%)	68.0	8.5	79.0	83-95
	Developing Stage	Mid-Mid high	Low	Mid-Mid high	High-Ultra high
Characteristics of Pilot Fields		High oil Viscosity; High levels of divalent cations	Block Reservoir; Polymer injeciton at low Water Cut	The most similar to onshore oilfields	Light oil; Good water; thin Layers; uncompartmentalized oilfield

Table 1.
Comparison of the three offshore chemical flooding fields with Daqing Field.

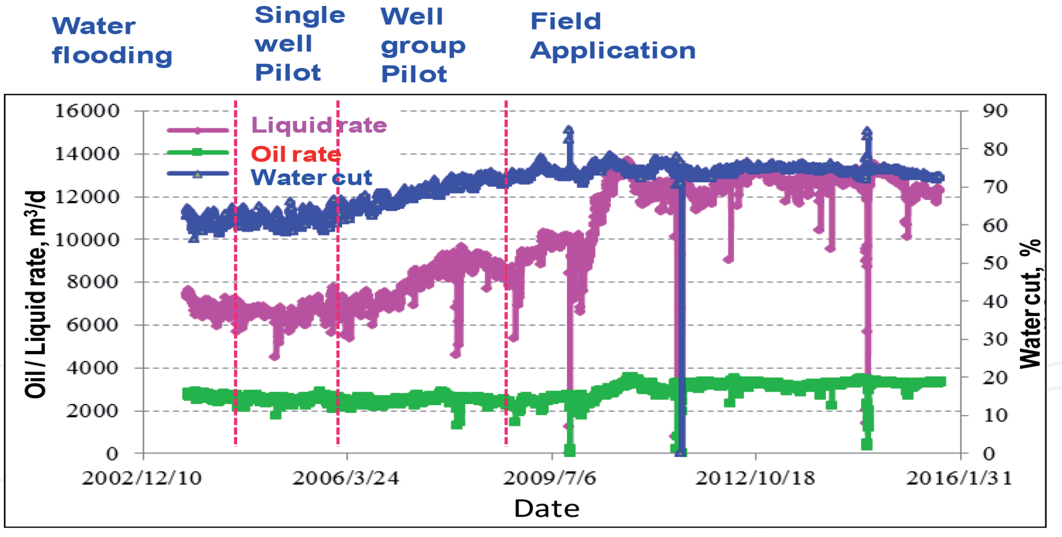

Figure 6.
Field production curves in S field.

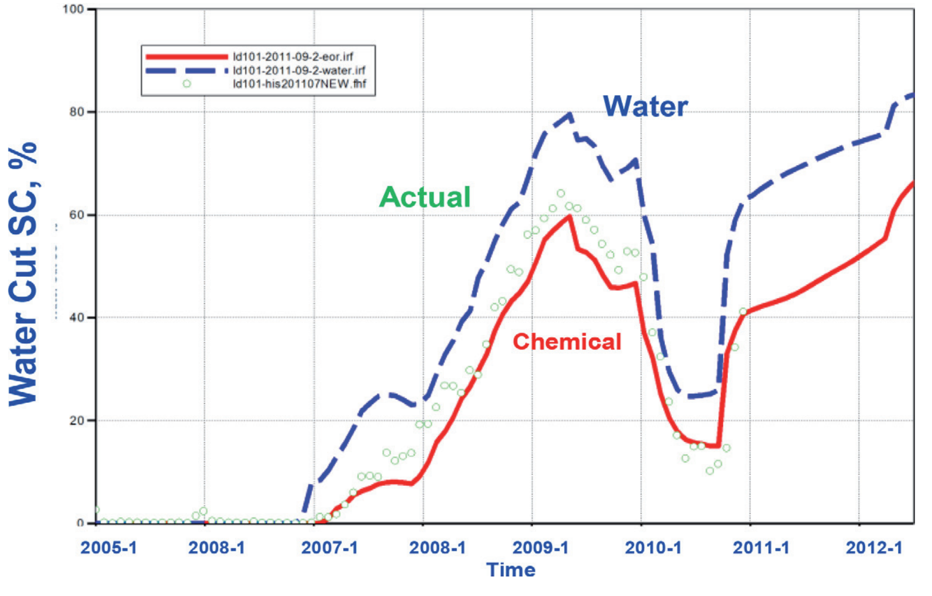

Figure 7.
Water cut curves under water flooding, chemical flooding, and actual situation.

injection pilot test was carried out since 2006 when the water cut in the pattern was lower than 10% [22–24]. After that, another five water injectors were converted to polymer injectors from 2007 to 2009. For the early-stage polymer flooding, the characteristics of the responses on producers were different from the case in which polymer flooding was conducted during high water cut stage. The water production of the producers continued to rise up after polymer flooding, but the simulation research showed that the water cut increasing rate was lower than the rate during water flooding. Of course, water cut drop was observed in some wells (**Figure 7**). By December 2014, the total incremental oil by polymer flooding was about 754,650 m^3, and the stage oil recovery was enhanced by 3.0%. The polymer flooding is still effective, and more incremental oil will be obtained later.

4.3 Chemical flooding in JW field

The water depth of W oil field is from 6.5 to 10.5 m; the reservoir depth is 1600–1800 m with banded fault anticline structural form and 25 m average effective thickness. This reservoir has normal temperature and pressure system containing oil with

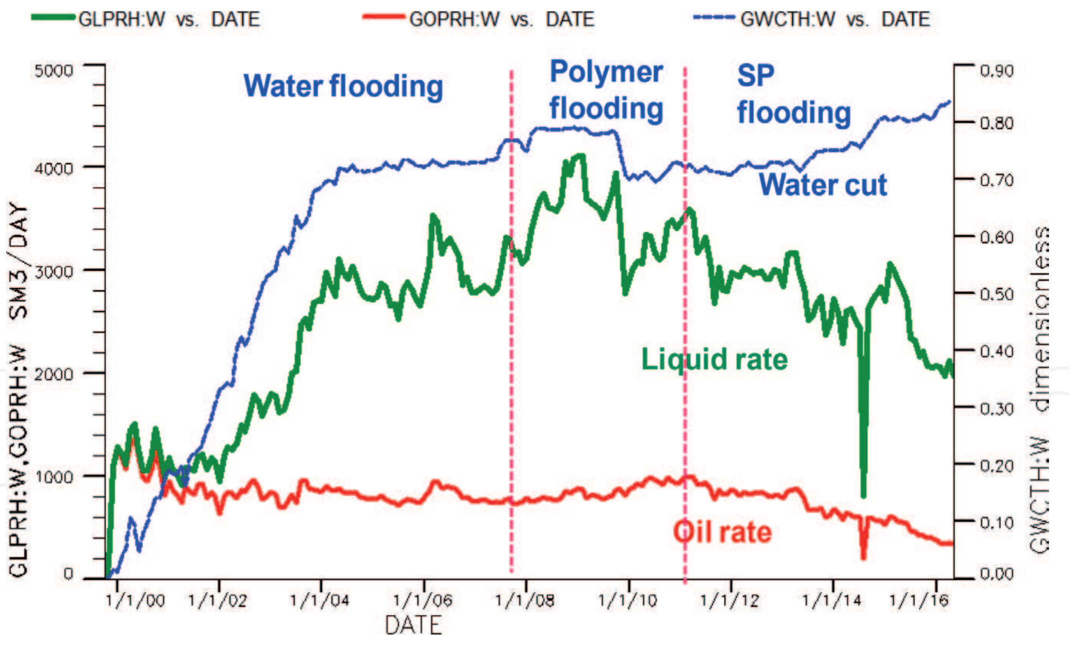

Figure 8.
Field production curves in JW field.

underground density of 0.87 g/cm^3 and reservoir viscosity of 16–26 mPa s. The formation porosity is from 22 to 36% and permeability from 0.01 to 5 μm^2. There are many sub-reservoirs in the upper part of this oil field, with large permeability difference and serious heterogeneity [25, 26]. W oil field was put into production since 1999 with anti-nine-spot well pattern and 350–400 m well space. Water flooding began in December 2000. This oil field was considered as the best candidate for polymer flooding which has the lowest water salinity and medium oil viscosity in Bohai Bay. In order to improve the efficiency of water flooding and reduce the decline rate of production, eight polymer injectors were gradually implemented at field water cut of 79% since 2007. The injection rate was 0.045 PV/year, and the polymer injection concentration was 1200 mg/L. After polymer flooding, the characteristics of polymer flooding such as decreasing water cut drop, increasing oil production, and injection profile improvement were observed gradually. In order to improve the performance of chemical flooding, eight polymer injectors were transferred into polymer-surfactant injectors since February 2011. The field water cut was successfully controlled, and the oil recovery was further improved (**Figure 8**). By the end of 2017, oil recovery had increased by 5.5%.

5. Prospect of offshore chemical EOR potential

At present, the offshore chemical flooding technologies represented by polymer flooding and surfactant-polymer flooding have achieved successful field tests and applications in China, and their technical reliability and economic effectiveness have been confirmed. However, it still faces some important challenges, including how to affordably develop the movable heavy crude oil with formation viscosity above 150 mPa s, how to effectively contain the water channeling to further improve oil recovery, how to achieve efficient treatment of polymer-bearing produced fluid on offshore platforms, etc. Therefore, it is necessary to continuously explore and develop novel offshore chemical flooding technologies, such as the heavy oil activator flooding, intelligent chemical flooding, and their combination technology.

As for the field application of the offshore chemical flooding in China, the cumulative oil increment is estimated to be 8.23 million cubic meters in the three oil fields currently performed. The total economic benefit is 9.3 billion yuan, and the input-output ratio is 1:3.7. In addition, according to the present offshore chemical potential evaluation and plan, 41 reservoir units are suitable for chemical flooding in Bohai Bay, whose oil recovery could be improved by 6.53% according to prediction [27, 28]. At the same time, China offshore chemical flooding technology and field applications provide valuable and practical reference for domestic and overseas counterparts. TOTAL and Chevron have, respectively, implemented polymer flooding tests in fields in West Africa, the North Sea, and Malaysia [28]. All of these attempts will further promote the progress of offshore chemical flooding and provide technical support for enhancing oil recovery in offshore oil fields.

6. Conclusions

1. Offshore chemical flooding technology system has been preliminarily established in China including high-efficiency development model, chemical flooding agents, platform injection system, and produced liquid treatment technology.

2. Field tests and applications were successfully carried out in S, L, and J oil fields since 2003, and expected oil increment benefits have been achieved, which proved that offshore chemical EOR technology is feasible.

3. It has explored a new road for increasing the recovery rate of offshore oil field and provided a solid technical guarantee for the efficient development of offshore oil fields. With the expansion of the scale of offshore chemical flooding application at home and abroad, more and more considerable oil recovery will be achieved.

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References

[1] Lake LW. Enhanced Oil Recovery. Englewood Cliffs, New Jersey: Prentice Hall; 1989

[2] Guo H, Dong J, Wang Z, et al. 2018 EOR Survey in China-Part 1. In: SPE Improved Oil Recovery Conference; 14-18 April; Tulsa, Oklahoma, USA; 2018

[3] Sheng J, Leonhardt B, Azri N. Status of polymer-flooding technology. Journal of Canadian Petroleum Technology. 2015;**54**(02):116-126

[4] Sheng J. A comprehensive review of alkaline-surfactant-polymer (ASP) flooding. Asia-Pacific Journal of Chemical Engineering. 2014;**9**(4):471-489

[5] Baginski V, Larsen D, Waldman, et al. Logistic considerations for safe execution of offshore chemical EOR projects. In: SPE Enhanced Oil Recovery Conference; 11-13 August; Kuala Lumpur, Malaysia; 2015

[6] Zhou S, Han M, Xiang W, et al. Research and application of polymer flooding technology in Bohai bay. China Offshore Oil & Gas. 2006;**18**(1):1-10

[7] Zhang F, Jiang W, Shun F. Key technology research and field test of offshore viscous polymer flooding. Engineering and Science. 2011;**13**(5): 28-33

[8] Han M, Xiang W. Application of EOR technology by means of polymer flooding in Bohai oil fields. In: SPE International Oil & Gas Conference and Exhibition in China; 5-7 December; Beijing, China; 2006

[9] Zhou W, Zhang J, Feng G, et al. Key Technologies of Polymer Flooding in Offshore Oilfield of Bohai bay. In: SPE Asia Pacific Oil and Gas Conference and Exhibition; 20-22 October; Perth, Australia; 2008

[10] Zhu Y, Zhang J, Jing B, et al. Ageing effect on steady rheological behavior in oilfield water of water-soluble, hydrophobically associating polymer. Advanced Materials Research. 2013;**781-784**:431-435

[11] Xie K, Lu X, Li Q, et al. Analysis of reservoir applicability of hydrophobically associating polymer. SPE Journal. 2016;**21**(01):1-9

[12] Zhang J, Wang S, Zhu Y, et al. Study and pilot test of activator flooding for heavy oil. 26-28 March. SPE EOR Conference at Oil and Gas West Asia; Muscat, Oman; 2018

[13] Zhang J, Hua Z, Zhu Y, et al. Properties of activator with high molecular weight and its effect on viscosity reduction and desorption of heavy oil. China Offshore Oil and Gas. 2018;**30**(04):97-105

[14] Zhu Y, Zhang J, Zhao W, et al. Research on efficient polymer dissolving technology for hydrophobically associating polymer flooding on offshore platform. Applied Mechanics and Materials. 2014;**670-671**:290-294

[15] Chen W, Zhao W, Zhang J. Research on the efficient preparation method of the polymer solution in offshore oilfields. Oil-Gasfield Surface Engineering. 2017;**36**(5):20-23

[16] Zhang L, Zhang Y, Gong B. The development of a new reservoir simulator to model polymer flooding and advanced wells for enhanced heavy oil recovery in Bohai bay. In: Canadian Unconventional Resources and International Petroleum Conference; 19-21 October; Calgary, Alberta, Canada; 2010

[17] Chen H, Tang H, Duan M, et al. Oil-water separation property of polymer-contained wastewater from

polymer-flooding oilfields in Bohai bay, China. Environmental Technology Letters. 2015;**36**(11):1373-1380

[18] Xu W, Dai Z, Wen Z, et al. Problems in and measurements of the treatment of output liquid in typical offshore polymer injection oil fields. Industrial Water Treatment. 2016;**36**(7):93-96

[19] Kang X, Zhang J, Sun F, et al. A review of polymer EOR on offshore heavy oil field in Bohai Bay, China. In: SPE enhanced oil recovery conference; 19-21 July; Kuala Lumpur, Malaysia; 2011

[20] Luo X, Zhao C. Practices and experiences of seven-year polymer flooding history matching in China offshore oil field: A case study. In: SPE Reservoir Characterisation and Simulation Conference and Exhibition; 9-11 October; Abu Dhabi, UAE; 2011

[21] Kang X, Guo F, Li Y. Experience from polymer-EOR on offshore heavy oil field in Bohai Bay, China. Journal of Petroleum Engineering & Technology. 2013;**3**(1):14-19

[22] Li B, Kang X, Zhang J, et al. A systematic study of the effect of plugging on polymer flooding in W offshore oilfield of Bohai Bay. In: SPE Improved Oil Recovery Conference; 14-18 April; Tulsa, Oklahoma, USA; 2018

[23] Kang X, Zhang J. Surfactant polymer (SP) flooding pilot test on offshore heavy oil field in Bohai Bay, China. In: SPE Enhanced Oil Recovery Conference; Kuala Lumpur, Malaysia; 2-4 July; SPE-165224-MS; 2013

[24] Lu Q, Ning Y, Wang J, et al. Full field offshore surfactant-polymer flooding in Bohai Bay China. In: SPE Asia Pacific Enhanced Oil Recovery Conference; 11-13 August. Kuala Lumpur, Malaysia; 2015

[25] Ma K, Li Y, Wang L, et al. Practice of the early stage polymer flooding on LD offshore oilfield in Bohai Bay of China. In: SPE Asia Pacific Enhanced Oil Recovery Conference; 11-13 August; Kuala Lumpur, Malaysia; 2015

[26] Xie X, Kang X, Zhang X, et al. Chemical flooding potential evaluation method in offshore heavy oil fields and its application. China Offshore Oil and Gas. 2016;**28**(1):69-74

[27] Yu B, Xia Z, Du Q. Evaluation method and software development for oilfield chemical flooding potential. Journal of Yangtze University (Natural Science Edition). 2016;**13**(26):46-49

[28] Morel DC, Jouenne S, Vert M, et al. Polymer flooding in deep offshore field: The Dalia Angola case. In: SPE Annual Technical Conference; 21-24 September; Denver, Colorado, USA; 2008