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Full Length Research Paper

Development of enhanced oil recovery in Daqing

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Chemical flooding is playing an important role in stabilizing oil output in Daqing, which is the largest field in China and started its chemical floods since the last 90's. In Daqing Oilfield, the chemical flooding annual output has exceeded 17 million tons; water cut has been dropped down significantly. The success of chemical enhanced oil recovery (EOR) has encouraged the increasing of chemical flooding projects largely in recent years. As a result of investment increase and experience build up, the technology of chemical flooding has been improved, especially polymer injection. The successful experience of Daqing is valuable for the development of chemical flooding EOR in other fields and countries.

Key words: Chemical, polymer, enhanced oil recovery, Daqing.

INTRODUCTION

Early in 1964, Sandiford (1964) first released his research which indicates the mobility of water used in water flooding was greatly reduced by the addition of very small amounts of partially hydrolyzed polyacrylamide (HPAM). Many additional papers sustaining and extending this idea have been published (Du, 2004; Gao and Towler, 2012). In the past forty years (Chauveteau, et al., 1988; Chu, 1994). Researchers around the world have carried out extensive investigation on the mechanism of polymer flooding and laid a solid foundation to the field scale application of polymer flood. Also many field scale polymer flooding projects have been put into production. However, few large-scale successes with these processes have been reported, except in China (Chang et al., 2006; Gao and Feng, 2012). Daqing Oilfield, the largest field of China, is a typical example of chemical flood, especially polymer flooding. Daqing Oilfield started industrial scale polymer flooding since 1996. The oil production rate of Daqing field by polymer flooding has rapidly increased since then (Wang et al., 2002; Feng et al., 2010). The annual oil production from the polymer flood has exceeded 10 million tons (Wang and Liu, 2006). It has become the key technology in stabilizing oil production of Daqing.

In the early years of this century, as the oil price in the international market dropped, the study on enhanced oil recovery in many major oil-producing countries was slowed down. Some pilot tests were suspended since operators stopped investing into the research work.

However, in China the rapid development of economy needs tons of energy to support it. It is important to shift the relying of energy on imported oil. It is essential to increase the oil production of oil fields. Most oil fields in China are developed by water flooding. In Daqing, the recovery efficiency of water flooding is relatively low. Water cut in most mature field is over 80% because of the heterogeneity of reservoirs and high viscosity of oil. The study on enhanced oil recovery had been carried out for more than 10 years before the first commercial injection. Now, notable progress has been made in chemical flooding (Lou and Yang, 1993; Delamaide, et al., 1994). Polymer flooding study focused on the displacement efficiency of polymer PAM, numerical simulation, field project design and prediction technique, which have been used for oil production of industrial scale based on numerous pilot tests. A biopolymer Xanthan gum agent was developed based on Daqing's condition, which can be used under the conditions of high temperature 80°C and high salt concentrations 170,000 ppm. It has been used successfully for profile control of injection wells and is being prepared for pilot flooding test. For the study on surfactant flooding, we have reached successfully the theory and technique of micro-emulsion flooding and micellar flooding is being used for pilot flooding. Recently, alkaline–polymer (AP) and surfactant–alkaline–polymer (SAP) flooding techniques have been developed. The pilot tests of these new chemicals have been conducted successfully (Liao, 2004; Li et al., 2006), that is, in a development test area abandoned, the pilot test's results of evident increase recovery factor and evident decrease in water cut has been achieved (Gao et al., 2010). Meanwhile, non-preflush chemical flooding technique has been developed to manage the chemical injection in the reservoirs with high clay content. The development and production of chemical flooding reagents make it possible to displace reservoir oil with lower cost. Now, we can produce different types of oil field chemical reagents, such as PAM, Xanthan gum, petroleum sulfonate of sodium, etc.

EXPERIENCE BUILD UP

Daqing Oilfield is a large fluvial sandstone reservoir onshore oilfield. In the 20 years' practices of polymer flooding, Daqing Oilfield has developed a complete series of techniques covering reservoir, production, facilities engineering and produced liquid treatment. Polymer flooding has gradually become an important technique to stabilize production capability of Daqing Oilfield. 13 field tests have been conducted successfully since 1989. There are 37 polymer flooding areas which contain nearly 9000 wells by the end of 2005. Polymer flood production has achieved 1×10^9t/a in the Daqing Oilfield. All the polymer flooding areas get good results of significant water-cut drop, great oil production increase, significant recovery rate increase. Almost every area's water-cut drop more than 20%, even reaches 35% in an area. Compare with water flooding, the recovery rate improve more than10%, with high concentration polymer flooding, the recovery rate is higher.

Based on the research and evaluation, Daqing's reservoir is suitable for polymer flooding. Firstly, Daqing Oil Field is a terrestrial fluvial-delta deposit, and it is mainly fining upward and multi-interval and multi-rhythm with a permeability variation factor between 0.635 and 0.71, which is within the maximum range (0.72) of polymer flooding for enhancing oil recovery. Secondly, Daqing reservoirs have a lower formation water salinity about 7, 000 mg/L which helps polymer solution keep higher viscosity in the reservoir and decrease oil - water mobility ratio greatly.Thirdly, because of the shallow buried oil reservoir and its low temperature, there is no thermo-oxidative degradation with polymer in the reservoir, and therefore economic benefits can be greatly improved due to saving of oxygen exclusion equipment; Fourthly, the result of polymer flooding is closely related with crude oil's viscosity which affects the result if it's too high or too low and at the same geological condition, there is an optimal viscosity range. Crude oil's viscosity in Daqing is about 9 mPa•s which is within the best range of polymer flooding (Niu, 2004).

Based on improving volumetric sweep efficiency and reducing channeling and breakthrough, polymer flooding can yield a significant increase in oil recovery when compared with water flooding. Polymer flooding has been conducted successfully in 13 field tests since 1989 and has been commercially used in the following years. Field tests show that the recovery improved with increasing concentration and injection volume. By applying polymer flooding, the main formation recovery of Daqing Oilfield has reached more than 50%. It is 10% ~ 15% higher compared with other oilfields. In the 20 years' practices of polymer flooding, Daqing Oilfield has developed a complete series of techniques covering reservoir, production, facilities engineering and produced liquid treatment. Polymer flooding has gradually become an important technique to maintain the high and stable production capability of Daqing Oilfield. Daqing oilfield, being the largest polymer flooding field in the world, has 37 polymer flooding areas which contain nearly 9000 wells by the end of 2005. Now, polymer flood production has achieved 1×10^9t/a in Daqing Oilfield. In this paper, the reservoir condition, pilot test, solution production and injection, production technology and produced liquid treatment technology are described.

Because of the complicated geological conditions in reservoir formations and a widespread distribution of small volume dentrital rocks in the reservoirs, the development of most oil fields in China is being limited by means of the natural water flooding. Instead, the water injection flooding method is employed extensively in these fields.

Laboratory research began in the 1960s, investigating the potential of enhanced oil recovery (EOR) processes in the Daqing Oilfield. For polymer flooding technology, from a single-injector polymer flood with small well spacing began in 1972. During the late 1980s, a pilot project in central Daqing was expanded to a multi-well pattern with larger well spacing.

Favorable results from pilot tests showed that polymer flooding was the one of the most efficient methods to improve areal and vertical sweep efficiency at Daqing, as well as providing mobility control. Consequently, the world's largest polymer flood was implemented at Daqing, beginning in 1996. By 2007, 22.3% of total production from the Daqing Oil Field was contributed by polymer flooding. Polymer flooding should boost the ultimate recovery for the field to over 50% original oil in place (OOIP) with and incremental recovery of 10~12% of OOIP. At the end of 2007, oil production from polymer flooding at the Daqing Oilfield was more than 10 million tons (73 million barrels) per year (sustained for 6 years). Recently, the industrial application has been expanded into the second-class, less-permeable strata.

POLYMER FLOODING

Because of the research efforts devoted in the last two

Table 1. Basic data of polymer flooding pilots.

Pilot	Pattern	Injector	Producer	Distance between injector and producer (m)	Date of injecting	Quantity of injected polymer (ppm × pv)	Dh %OOIP.	Benefit of polymer (ton/ton)
Daqing-x1	Inverted five-spot pattern	1	4	75	1972–1973	163 = 0.2	5.1	153.4
Daqing-HP	Inverted five-spot pattern	4	9	200	1988–1990	272 = 0.3	4.3	81.8
Daqing-PO	Inverted five-spot pattern	4	9	106	1990–1992	506 = 0.3	14	177
Daqing-PT	Inverted five-spot pattern	4	9	106	1990–1992	496 = 0.3	11.6	209
Daqing-G4K	Irregular pattern	3	11	100-160	1986–1989	–	12.7	400

Table 2. Basic data of semi-industrial and industrial projects.

Project	Area (km^2)	Well pattern	Injector	Producer	Distance between injector and producer (m)	Date of injecting
Daqing-G4K	0.86	Irregular pattern	6	12	100–360	1991
Daqing-TP	3.13	Inverted five-spot pattern	21	36	250	1993
Daqing-LP1	1.45	Inverted five-spot pattern	16	25	212	1994
Daqing-LP2	2.09	Inverted five-spot pattern	9	26	300	1994
Daqing-G3E	0.81	Irregular pattern	7	11	100–360	1994
Daqing-G3W	1.03	Irregular pattern	7	18	100–360	1991

decades, experience has been built up, which covers the reservoir engineering, oil recovery mechanisms, solution properties, physical and numerical simulations, and the efficient prediction method of the polymer flooding technology (Gao and Towler, 2011). Based on these laboratory researches, the pilot plant tests have been conducted in several oil fields of various reservoir types, and therefore, have had much experience in commercial fulfillment, like engineering design, surface construction, testing and analysis methods, dynamic control method of drilling and the tracer injection technology (Liu, 1991; Wang et al., 1991; Gao et al., 2010). Since the results obtained from semi-industry tests provide a positive answer for the polymer flooding method, after 1993, this method has been industrialized in our oil fields.

Pilot tests

Table 1 summarizes the test results obtained by the application of the polymer flooding method in the different oil fields of various types. It is found that the polymer solution can apparently improve the trial formatted crude oil from these oil fields always coefficient, consequently, reducing the water cut in these oil reservoirs of heterogeneous geological conditions. The polyacrylamide polymer is used in these oil fields. The reservoir water of law mineralized degree and a not quite high reservoir temperature assure that this polymer can increase the viscosity of the oil-water solution in the reservoir efficiently. Usually, with the injection of 350~380 ppm pore volume polymer solution, there is an increased profit of 150~200 tons oil production obtained for per ton of polymer injected, and the oil recovery efficiency will be increased in the ranges of 4~14% of OOIP.

Commercial projects

In these projects, we have enlarged the distance between the injection wells and production wells to an average value greater than 200 m. The area involved in each project is larger than the previous one, one project's area is even bigger than 3 km^2, and more than 60 injection and production wells are located in this area. In each project, the water used in the injection or production wells is de-mineralized by the proper treatment technology. The effects of polymer injection are to reduce the water cut and increase sweep efficiency. The success of the pilot test enables us to carry out the semi-industry and industry EOR projects by using this polymer flooding method (Liu, et al., 1995).

Table 2 summarizes the projects executed currently in our oil fields. In these projects, we have enlarged the distance between the injection wells and production wells to an average value greater than 200 m. The area involved in each project is larger than the previous one, one project's area is even bigger than 3 km^2, and more than 60 injection and production wells are located in this area. In each project, the water used in the injection or production wells is de-mineralized by the proper treatment technology. The effects of reducing the water

Table 3. Basic data of combination flooding pilots.

Project	Pattern	Injector	Producer	Distance between injector and producer (m)	Concentration of chemicals			Incremental %OOIP.
					S	A	P	
Daqing -GD4	invertedfive-spotpattern	4	9	50	0.4	1.5	0.1	13.4
Daqing-SSP	invertedfive-spotpattern	4	9	106	0.6	1.25	0.15	20–26[a]
Daqing -2	irregularpattern	4	9	160–190		2	0.1	-

cut and increasing the oil production are observed at all of the production wells in these projects. For example, in the Daqing-TP project, it is found that the oil production is increased after injecting 60 ppm pore volume polymer solution on January 1993, and this increase is maintained until August 1994, at which, the water cut of that reservoir is decreased from 90.7 to 80.1% with a daily production of 1200 tons of oil among which, 408 tons oil is recovered by this polymer flooding method. At present, in the oil fields of our country, the polymer flooding technology has been fully industrialized and its achievement is very promising.

In order to have a sufficient supply of the polymer, a polyacrylamide chemical plant 30,000 tons per year will be opened in the near future (Liu, 1995). It is anticipated that this polymer flooding.

The success of the surfactant–polymer flooding method is proven by the positive results obtained from the past and current pilot tests in our oil fields. However, because of the high consumption rate of surfactant by the micellar solubilization effect, it is found that this surfactant–polymer combination flooding method is not economically feasible in practice. In order to overcome this v high consumption disadvantage, combining with the advantages of the flooding methods of using surfactants, polymer and alkaline solution, we have been developed the alkaline–surfactant–polymer A–S–P. combination flooding method and the alkaline–polymer A–Pcombination flooding method for crude oil with high acid value (Song et al., 1995), and the surfactant–alkaline–polymer combination flooding methodfor crude oil containing natural organic acid (Yang et al., 1995a, b). Because of the characteristics of a higher viscosity value, and also the surface active ability, these kinds of oil-recovery reagents are able to increase the mobility ratio and the displacement efficiency, and therefore, can decrease the interfacial tension efficiently at the oil–water interface. The oil recovery efficiencies of these combination flooding methods are at least one time as high as that of polymer flooding method. Meanwhile, these oil recovery reagents can also combine with the organic acids on the surfaces of crude oil to form the local surface active reactants and when these reactants meet again with the surfactant molecules in the injected reagents, the coordination effect will result, consequently, the effect of decreasing the interfacial tension becomes pronounced. The alkaline compounds in these reagents can also inhibit the retention loss of the injected chemicals. Thus, under the same displacement efficiency as that of surfactant–polymer combination flooding method, these A–S–P, A–P and S–A–P combination flooding methods will reduce the amount of surfactant consumed by more than 10 times, as well as the capital cost of the surfactants.

In China, we already have the chemical plants to produce these high surface active reagents. The price for the reactant resources of these surfactants is very cheap, and it is very easy to get these materials in our country. These surfactants can activate the surface properties of acid oil and non-acid oil simultaneously, and have the ability to form the ultra-low interfacial tension in a wide concentration range.

Table 3 gives the pilot test results of using these combination flooding methods in our oil fields currently. The pilot test result obtained from a successful injection. Before injecting the chemical slug, the test wells in this oil field belong to the economic-limited and highly developed ones, the water cut of these wells is above 98% and the oil recovery efficiency obtained by the water flooding method is about 54.4% of OOIP., but after injecting the A–S–P combination slug, the water cut of these wells is reduced significantly and the production of crude oil is increased. The increased oil recovery efficiency by this EOR technology is about 13.4% of OOIP.

In order to solve the high clay content problem in some reservoirs of Daqing, we have developed a non-preflush chemical flooding technique, at which the amount of surfactant adsorbed on the reservoir rock surface is reduced by the addition of polyelectrolytes. By using this technology, the pilot test results obtained from the Yumen Oilfield (Yang et al., 1995a, b) are very significant. Hence, according to thecharacteristics of the oil reservoirs, several injection methods have been successfully developed by combining different chemicals, which provide a very promising potential in increasing the oil recovery at Daqing.

CONCLUSION

The heterogeneity of the geological conditions in Daqing reservoirs causes a low oil recovery efficiency using the traditional water flooding technology.

The industrial experience of chemical injections in Daqing shows that the polymer flooding method can be applied successfully in variable reservoirs. Significant progress is obtained from the pilot tests and commercial injections by using the various multiple chemicalsflooding technologies, and these combination methods all have high potential in increasing the oil recovery efficiency.

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