Abstract

This work describes the results of laboratory experiments carried out on core samples and sandpack models as well as the field pilot tests conducted in October 2013 on 2 injection wells of Kumkol oilfield. The reduction of the permeability of porous space was achieved by injection of gellan solution, gelation of which is initiated by the following cations: Ba\(^{2+}\), Ca\(^{2+}\), Mg\(^{2+}\), K\(^{+}\), Na\(^{+}\), containing in brine water. On the basis of laboratory experiments the suitable concentrations of polymer reagent for the pilot tests were selected. A series of laboratory experiments were carried out to reduce the amount of polymer reagent without detriment to the efficiency of the technology. Also the mixtures of polysaccharides gellan and xanthan in the weight ratios 1:2; 1:1; 2:1 were found to be more effective in comparison with separate components. One of the main features of this work is that polysaccharide gellan was used for the first time in oil industry, thus new application frontier for this polymer was found. The most remarkable feature of the proposed polymer is due to its gelation after contacting with brine water so no additives are needed to initiate the gelation process inside of the oil formation in contrast to polyacrylamide gels crosslinked by chromium ions which are widely used for conformance control operations.

Introduction

As world population approaches to 7.5 billion people the consumption of energy resources constantly growth. To meet this demand petroleum companies are trying to find new methods for the extraction of undrained oil from mature oilfields. Mature fields give more than 70% of the world’s hydrocarbon production while the average recovery factor for oil is only 35%, thus increase of the recovery factor from these reservoirs is common target for petroleum companies [1]. Maintainance of reservoir pressure in oilfields is achieved by water injection. Water encroachment pattern is not always evenly distributed throughout the heterogeneous strata and as a result water breakthrough takes place in the production wells. Excess production of water through localized super-permeable channels is one of the main problems which have to be addressed in order to increase recovery factor for oil [2].

To increase macroscopic sweep efficiency of a reservoir, water injectivity profile should uniformly spread across the entire reservoir. This may be achieved by plugging of those super-permeable channels
and by redistribution of waterdrive into low permeability areas mobilizing hard-to-move pockets of unswept hydrocarbons [3]. For this aim polymer solutions have been used extensively. Injected polymer solution generally penetrates into high permeable zones and the relative permeability reduction takes place after the solution has been swelled or crosslinked in situ [4, 5]. Literature survey shows that a wide variety of polymer gel systems generally consist of: inorganically crosslinked and organically crosslinked polymer gels [6]. Partially hydrolyzed polyacrylamide (PHPA) crosslinked by Cr³⁺, Zr⁴⁺ and Al³⁺ is one of the examples of inorganically crosslinked gels that are widely used since 1970s [3]. Example of organically crosslinked polymer gel is copolymer of polyacrylamide tertiary butyl acrylate (PAtBA) crosslinked with polyethyleneimine (PEI) was also widely applied in the field for water conformance control worldwide [6, 7]. But these systems were thoroughly revised and prohibited to be used in some countries because of the negative impact of the crosslinkers on the environment [8]. Because of these issues, finding and practically adopting an environmentally friendly, single component polymer gel system is a focus of this study.

**Experimental part**

**Materials and methods**

In this study the newly introduced polymer is anionic extracellular polysaccharide gellan discovered in 1978. Gellan consists of tetrasaccharide units: 1,3-linked β-D-glucose, 1,4-linked β-D-glucoronic acid, 1,4-linked β-D-glucose, and 1,4-linked α-L-rhamnose as shown in Fig.1.

Aqueous solution of gellan undergoes sol-gel transition under certain temperature, pH and salinity [9, 10], this remarkable feature makes this polymer attractive for water profile leveling applications. Xanthan is an extracellular polysaccharide produced by fermentation of the bacterium *xanthomonascampestris*. Its low cost, high viscosifying ability, coupled with excellent stability under high salinity, high temperature, and mechanical shear conditions makes it suitable for enhanced oil recovery (EOR) [11]. Xanthan gum was kindly furnished by Xinjiang Fufeng Biotechnologies Co., Ltd. (Urumqi, China). Fluid samples used were brine water and crude oil from Kumkol oilfield (Republic of Kazakhstan). Brine water with density 1.05 g cm⁻³ and pH 6.68 was composed of 22.5 g·L⁻¹ of Na⁺ and K⁺, 3.8 g·L⁻¹ of Ca²⁺, 0.85 g·L⁻¹ of Mg²⁺, and 43.9 g·L⁻¹ of Cl⁻ ions. Crude oil density and dynamic viscosity at 55 °C were 795.4 kg m⁻³ and 2.679 mPa·sec respectively. Steel cylinder filled with sand was used to simulate the porous medium (Fig.2). These sand packs were composed of sand particles with granular size varying from 0.043 to 1 mm.
In each case gellan solution was injected into the previously waterflooded sand pack model. Water, oil and polymer solution were injected under the flow rate of 0.5 cm³·min⁻¹. And the injection pressure value was constantly registrated.

Results and Discussion

Laboratory testing for injectivity profile leveling operation (IPLO)

Analysis of the injection pressure curves allowed to reveal some peculiarities in hydrodynamic behavior of gellan aqueous solution which distinguish it from the other polymers used in oil industry and also to choose an appropriate concentration of the solution for the oilfield pilot tests.

The first series of experiments were aimed to select the appropriate concentration of gellan solution for the injectivity profile leveling operation (IPLO) in two injection wells on Kumkol oilfield. The pilot tests were conducted in two steps: 1) injection of low concentrated gellan solution to increase the overall sweep efficiency of the reservoir and to create gel plugged areas on the long distance from the injected well; 2) injection of high concentrated gellan solution to level the water injection pattern (profile) in the vicinity of the well. In our case 0.2 and 0.5 % gellan solutions were tested on the sand pack models, the experimental results are given in Fig. 3.

It is seen that independently on the permeability of sand pack model the higher concentration of gellan demonstrates the better plugging effect. Therefore it is suggested that 0.2% gellan solution is better to use for in depth permeability modification. While the 0.5% gellan solution is better to use as a permeability modifier in the vicinity of the injection well.

Performing of the field pilot tests

Aqueous solution of gellan was injected into two injection wells (No.3383 and 3065) on Kumkol oilfield, the total volumes of injected solution were 234 and 160 m³, respectively. One ton of dry polymer powder was spent for each well. In the course of injection of gellan solution the pressure increased from 55 to 90-95 atm indicating the reduction of the permeability inside of the reservoir. Response of the reservoir to the treatment was monitored through 6 producing wells located in the neighbourhood of the injectors. Effectiveness of the technology was estimated after 6 months. For each well the incremental oil recovery
was calculated by comparison of incremental line values with base line value. Base line value represents an average oil flow rate calculated for the last three months before injection. Base line oil flow rate value is extrapolated to the next 6 months after the treatment, and then this value is subtracted from the total value of really produced oil during this period of time. The well 2115 showed the most optimistic response to the treatment compared to the prehistory of oil flow rate (water flooding) (Fig. 4).

The incremental oil recovery for each well is presented in Table 1.

The negative increment for the well 2342 is explained by the fact that this reservoir has been waterflooded for more than 20 years, injection of gellan led to enhancement of oil production and to more severe depletion of the part of the reservoir adjacent to the injectors.
The effectiveness of the gellan injection was evaluated by comparison of the proposed technology with existing technologies (Table 2). As seen from Table 2, injection of 1 ton of dry gellan into the oil reservoirs produces 1,895 tons of incremental oil whereas the same amount of other reagents produces 88 - 380 tons of incremental oil. In 2009 the technological efficiency of polyacrylamide (PAAm) for IPLO on North Buzachi (West Kazakhstan) was 380 tons/ton, and this result was recognized as the best one throughout the world projects. However, the efficiency of gellan is 5 times higher than PAAm in spite of the fact that its cost is 2-3 times higher than PAAm. Thus, the pilot test results on Kumkol oilfield (Kyzylorda region, Kazakhstan) confirmed that the solution to major challenge facing water shut off effectiveness is the excellent gelation ability of gellan in high saline oilfield water and plugging of high permeable channels.

Alternating injection of gellan and brine solutions
Unique property of gellan is to form gel structure through contacting with brine water. Therefore, alternate injection of gellan and brine water into the oil reservoir is expected to be more effective plugging way of high permeable channels. Since the gellan powder is dissolved in technical water with low salinity, the constant injection of gellan solution leads to the washing out of salt from the vicinity of the well. The gel formation takes place when the front edge of injected gellan solution meets the saline water (so called sol-gel transition) [16]. Due to permanent injection of gellan solution into the well, the salinity of oil reservoir gradually decreases. In its turn this causes formation of flowable weak gel that reduces the efficiency of plugging. It is expected that alternate injection of gellan and brine solutions will overcome this problem. To check this point, a series of filtration experiments were conducted on sand pack models possessing the high permeability 2 Darcy. Experiments consisted of alternating injection of 10 cm$^3$ of 0.5 % gellan solution and brine water into the waterflooded sand packs. The dependence of injected pressure on pumped volume was compared with constant injection of gellan (Fig. 5).

It is clearly seen from Fig. 5 that each portion of injected gellan solution is followed by the injection of brine water portion. Alternate injection of gellan and brine solutions leads to gradually increase of the injection pressure. The reasonable explanation of this phenomenon is permanent formation of gel slug inside of the sand pack. Fig. 6 clearly demonstrates that alternate injection of gellan and brine solutions gives the same effect if only gellan solution will be injected. The difference between the constant injection of gellan and alternating injection of gellan and brine solutions is small in the context of pore space plugging.
Thus by the alternating injection of gellan and brine solutions it is possible to reduce the amount of injecting reagent at least two times without detriment to the efficiency of the technology. This approach will considerably reduce the cost of the project.

**Injection of gellan and xanthan mixtures**

One of the disadvantages of gellan is its high cost. So it is worthy to study whether mixture of gellan and xanthan is applicable for conformance control or not. To decrease the total cost of the polymer flooding technology the mixtures of gellan and xanthan with weight ratios of [gellan]:[xanthan] = 2:1; 1:1 and 1:2 were tested. Three core flooding experiments were conducted to study the dynamic plugging properties of aqueous solutions of gellan and xanthan mixtures (Fig.7). The concentration of gellan and xanthan mixtures was kept constant and equal to 0.5%.

Aqueous mixtures of gellan and xanthan prepared at the weight ratios of 1:1 and 1:2 behave similar plugging properties while excess of gellan component in the mixture (2:1) shows the better plugging ability and may be used for conformance control. For the low permeability rocks it is recommended to use the mixtures of [gellan]:[xanthan] with weight ratios 1:1 and 1:2 while for conformance control of the high permeable channels the mixture of [gellan]:[xanthan] = 2:1 should preferentially be used. From economic point of view the application of the mixtures of gellan and xanthan reduces the cost of reagents by 22%.

**Conclusions**

The unique property of gellan to form gel through contacting with salt may be applied for alternating injection of gellan and brine solutions to create the gel slugs inside of the reservoir. As a result the cost of polymeric reagent may be reduced two times. Depending on in-place permeability the optimal composition of gellan and xanthan may be used for the plugging of high or low permeable channels. Enriched by gellan mixture is effective for plugging of high permeable zones. Equimolar or enriched by xanthan mixture is suitable for conformance control of low permeable channels. Moreover, the application of the mixtures of gellan and xanthan reduces the cost of reagent by 22%. The results of pilot test conducted at Kumkol oilfield showed that polysaccharide gellan can be adopted as a new highly effective IPLO agent for injection wells on mature oilfields. Efficiency of gellan was compared with existing polymer gel systems used in oil industry. Comparative analysis demonstrates that the effectiveness of gellan is 5 times higher than the best result registered in 2009. It is expected that our laboratory and oilfield tests will open a new world for environmentally friendly gellan application in EOR.

**Acknowledgments**

This work was performed in the framework of Technology Commercialization Project (Grant No. 161 for Senior Scientific Research Group). Financial support from the Ministry of Education and Science of the Republic of Kazakhstan and World Bank is greatly acknowledged.

**References**

1. Maximizing the Value of Mature Fields. 05/2012 HALLIBURTON, Solving challenges.


12. Ч. Сунь, И. Шагирбаев, С. Лобанов и др.: “Научно прикладные аспекты проекта по гелеполимерному заводнению на месторождении Северные Бузачи.” ООО «РН-УФАНИПИНЕФТЬ».


