Evaluation of enhanced oil recovery efficiency at fields with hard-to-recover reserves

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Abstract. The paper discusses measures of enhanced oil recovery of highly watered reservoirs using water-soluble polymer-based systems at Priobskoye oilfield. The application is based on enhanced oil recovery of reservoirs due to decrease of permeability of water channels due to internal formation of insoluble sediments when mixing the solution of alkali with highly mineralized reservoir waters. The study revealed reserves for oil production due to the injection of polymer-alkaline solution.

1. Introduction

At the current stage oil industry is facing a decrease in the efficiency of field development. A decisive factor in this trend is a significant increase in the share of inefficient, hard-to-recover reserves. This is caused by the fact that many highly productive deposits and fields are characterized by the late stages of their development, as well as the unfavorable qualitative characteristics of oil reserves of deposits and fields re-introduced into the development.

Given the current situation, it should be recognized that only a large-scale, widespread introduction of new technologies that increase the efficiency of conventional flooding will reduce the rate of oil production decline. Therefore, every year there is an increased attention to methods of enhanced oil recovery, which programs and projects of development and application are mainly focused on the expansion of physicochemical recovery methods.

Western Siberia fields are characterized by a great number of reservoir beds, development of interlayers not consistent in area and section, uneven and often low permeability, and low initial oil saturation. During the development process, these factors cause the production of oil reserves of highly permeable areas, and, as a result, a premature increase in watering and a decline in oil production levels. In this regard, the current direction of enhanced oil recovery is the use of technologies aimed at equalizing the input profile, reducing water inflows to the bottoms of production wells. In recent years one of the most effective methods at Priobskoye field has been the injection of polymer-alkaline solution. Enhanced oil recovery is an urgent problem, the solution of which will affect the efficiency of geological exploration, oil production and economic potential of the region [1].

2. Materials and methods

One of the main problems of the oil and gas industry is inefficient subsurface management. The strategic goals require the development and implementation of modern methods of enhanced oil recovery.

High water production is also an urgent problem, as a result of which the cost of production increases,
as well as the corrosion of pipelines and equipment.

Currently, a large number of different methods of enhanced oil recovery (EOR) are used:
- thermal methods – heat input or its generation directly in the productive deposit. These include steam injection technologies (cyclic or continuous), hot water injection, fireflooding;
- gas methods – injection of carbon dioxide CO₂, nitrogen N₂, hydrocarbon and flue gases into the reservoir;
- physicochemical methods – injection of reagents into the reservoir that reduce interfacial tension to reduce the degree of oil blocking in hydrophilic rocks. They include solutions of polymers and other chemical reagents, which are most often intended to change filtration flows and equalize the input profile [2].

The report of the International Energy Agency states that the main criteria for choosing EOR methods are as follows: rock type, depth, density and viscosity of oil, current recovery ratio, permeability and temperature.

According to a review by Ernst & Young, thermal EOR methods in the world account for 42% of all projects, physicochemical – 31%, gas – 27%. In Russia, the most developed methods include physicochemical EOR, due to which the share of oil production exceeds 80% of the gross output [3, 4].

Polymer exposure technologies are widely utilized in Russia using such polymer reagents as Xanthan and Product BP-92 biopolymers, Gipan hydrolyzed polyacrylonitrile, polyethylene oxides, polymers based on methacrylic acid, polyacrylamide (PAM) technologies.

The main methods of using polymers in enhanced oil recovery technologies include the following:
- use of agents that reduce the ratio of water to oil mobility (polymer flooding);
- use of cross-linked polymer systems that can be cross-linked both in the formation at depth and in the bottomhole treatment in order to block high permeability zones.

An important factor of enhanced oil recovery during flooding is the ratio of viscosity of oil and injected water. When a high-molecular polymer is added to the injected water, the viscosity of the displacement fluid increases, thereby making the oil displacement front more uniform. Almost all initial polymer flooding projects partially used hydrolyzed polyacrylamide (GPAM) due to the large molecular weight, which increases viscosity, and anionic repulsions between polymer molecules and segments of one molecule lead to stretching and bonding of molecules, as a result of which the mobility of the solution is also reduced. Polyacrylamide is able to reduce mobility in the porous medium to a greater extent than when measuring viscosity under standard conditions, which is associated with elastic turbulence at a loss of stability of the polymer solution flow in the porous medium and leads to a multiple increase in filtration resistance. At the same time, the transition of polymer solution from a pore channel to a pore is accompanied by pulsation of filtration rate and leads to more complete oil extraction.

During the movement of the polymer fringe, PAM is adsorbed by the rock, the value of which under static conditions is 0.1-0.2 mg/g for quartz sand, 0.45-0.55 mg/g for sandstone and limestone. The polymer solution first enters the highly permeable channels and narrows them by adsorption, which leads to a decrease in water permeability and an equalization of the dynamic inhomogeneity of fluid flows. However, minimal adsorption of the polymer by rock is one of the basic requirements, since this may lead to a loss of mobility control and formation of an oil bank [5].

The restrictions on the use of this technology include:
- temperature greater than 90°C, at which the destruction of polyacrylamide begins;
- high mineralization of reservoir water, in which the structure of the polymer solution is destroyed;
- injection of polymer solution into low permeability reservoirs (permeability less than 0.04 μm²) may not be technically feasible due to high pressure;
- polyacrylamide is subject to mechanical degradation when exposed to high shear loads, especially when passing pumps, valves and orifices.

According to the results of laboratory and field tests, polymer flooding is recommended only at an early stage of field development.

Besides, the use of cross-linked polymer systems has become widespread. A crosslinker is added to
the polymer solution, which binds the polymer molecules to each other and to the pore walls. Polysaccharides, hydroxyethylcellulose, polyacrylamide may be used as polymers. Polyvalent metal cations (chromium, aluminum, iron) are used as crosslinking agent.

This technology made it possible to reveal that it is not always possible to pump the formed gel into formation sections remote from the bottomhole zone. Since the gelling time is a very important parameter, the key solution to this problem is to control the gelling time by varying the concentrations of a polymer and a crosslinking agent, as well as the pH medium.

At the present stage, there is a constant complication of oil production conditions, which leads to higher requirements for the applied polymer reagents and the need to develop new approaches to their creation. The production of hydrocarbons in low-permeability reservoirs seems quite interesting due to the huge oil reserves contained in them. Since the oil recovery rate from low permeability reservoirs is lower than from medium and high permeability reservoirs, it is necessary to use nanostructured reagents with unique penetrating ability. However, the growth of nanoparticle-based technologies almost did not affect the oil industry in Russia, while the existing methods for the synthesis of nanomaterials on various bases have competitive advantages over the synthesis of existing reagents. According to experts, the ability of nanoparticles to penetrate into the smallest pores of oil-saturated reservoirs will allow utilizing huge reserves of oil, the production of which at the present stage with the use of existing technologies is not possible [6].

Pre-crosslinked polymer nanoreagents forming a gel at a given distance from the bottomhole zone of the formation undergo much less mechanical destruction when passing through surface equipment. The effect of using such a technology may last for 1.5-2 years, while the effect of using various viscoelastic compositions is observed for six months.

The need for flood control technologies is caused by advanced water displacement and watering of certain interlayers. This is caused by high layered heterogeneity of productive formations in terms of permeability, joint operation of monolithic high-permeability sandstones and low-permeability interlayers, and the advance of water through oil-saturated intervals in the oil-water contact (OWC) zone.

In 2012, in order to plan the application of recovery methods at the oilfields of Gazpromneft-Khantos LLC, geological and hydrodynamic models of deposits were created, which are used to analyze the structure of current oil reserves and clarify the technological efficiency of recovery methods in various field conditions, such as:

- flooding;
- flooding using surface acting agents (SAA);
- injection of alkali fringes;
- polymer flooding;
- water-gas stimulation (WGS);
- hydraulic fracturing;
- thermophysical and thermochemical treatment.

The most common way to affect the formation is flooding. Flooding as a separate method of development under favorable physical and geological conditions allows achieving an oil recovery coefficient of 0.65-0.7. However, when flooding in low-permeable reservoirs, the composition and properties of rocks and water become important. Swelling is possible or clogging of the bottomhole zone with sediment during interaction with injected water. All this reduces the flow properties of the formation. As foreign experience shows, the nature of rock wettability has a special influence on the displacement mechanism during flooding. In a low-permeability reservoir, displacement proceeds only from large channels. Clay materials capable of swelling from contact with water are important.

In view of these problems, flooding using SAA was used at Priobskoye field.

Nonionic SAA of OP-10 type at optimal weight content of about 0.05-0.1% reduce surface tension from 35-45 to 8-7 mN/m, increase the wetting angle from 18 to 27° and decrease the wetting tension by 8-10 times. However, such solutions are capable of increasing oil recovery by not more than 2-5%. Moreover, low permeability of the reservoir adversely affected the SAA efficiency. Besides, this process
is quite expensive. Therefore, this method did not find further application at Priobskoye field.

The next method considered for use was alkaline flooding. This method is based on the interaction of alkalis with active components (organic acids) of oil and rock. In this case, SAA is formed, the wettability of the rock changes, clays swell, stable emulsions are formed and precipitations are released.

Alkaline flooding was abandoned in the conditions of Priobskoye field as this can destroy the rock matrix. When alkali interacts with mineral rocks, it can lead to ion exchange and salt formation. The reservoir of Priobskoye field is considered loamy, when alkali interacts with clay minerals, clays swell and permeability decreases.

The method of polymer flooding was also considered. This method is based on the ability of the polymer solution in water to reduce the ratio of mobility (water thickening) of oil and water (current resistance factor), to reduce the mobility of water pumped behind the polymer solution (residual resistance factor), which increases the coverage of formations by flooding.

Polymer flooding is very sensitive to geological and physical conditions of the reservoir and the properties of formation fluids. The use of the method is limited by the formation temperature, and therefore its use at Priobskoye field requires careful justification.

Under these conditions, water-gas stimulation (WGS) may be more effective. Water-gas stimulation (WGS) implies the injection of gas and water into formations in a certain sequence and in certain ratios. The main mechanism of WGS is to increase the coverage of the formation by the process of oil displacement with simultaneous increase of the oil recovery factor. The coverage of the formation by displacement increases due to the formation of extensive zones of three-phase filtration of oil, gas and water in the most permeable zones and interlayers of the formation. Thus, the displacement front is leveled. The oil recovery factor is increased due to two factors: stabilization of oil-displacement fluid at micro level and additional washing of separate oil globules due to periodic change of the displacement phase, as well as conditions of surface wetting of a porous medium [7].

The next recovery methods were thermophysical and thermochemical treatment.

The treatment of the bottomhole zone with a powder pressure generator (PPG) is called thermochemical treatment. Upon explosion of the generator charge, which is usually just above the perforation interval, powder gases are formed, directed downwards and acting under pressure and high temperature on the formation.

Only one of the 7 wells had a positive effect using PPG only. Oil production in well No. 227 increased from 3.0 to 8.6 tons/day. The effect lasted 3 months. It should be noted that the PPG was applied on salt solutions of well killing without treating the charge coupled device with dissolving compositions. The complication with hydraulic bailer treatment also did not give any effect. When combining PPG with other methods, positive results were obtained for some wells. Thus, the thermochemical effect of PPG with a hydrochloric acid bath in well No. 3720 (formation AS11) ensured an estimated increase in oil production of more than 30 tons/day.

Another thermochemical method was the ignition technology of combustible oxidizing compositions (COC) previously pumped into the charge coupled device using a standard powder pressure generator (PPG-BC 100, PPG-42, etc.). Combustible oxidizing compositions represent the composition of aqueous solutions of an oxidizing agent (ammonium nitrate) and a combustible (glycerin, carbamide, ammonphos, etc.), which are naturally fireproof. The ignition of COC using a powder generator provides a much longer (up to 15 seconds) pulse of high-energy impact on the formation compared to the standard impact of PPG-BC up to 2 seconds. As a result, vertical cracks up to 20 meters long are formed, which are fixed during the formation of combustion products.

One well – No. 368 was treated on the territory of the field. The production rate was about 30 tons/day, before the impact the well was running with a flow rate of 5.4 tons/day on average. The anhydrous nature of the influx has not changed. The method of thermogasochemical recovery is based on the combustion of solid powders in a liquid without any sealed chambers or protective shells. The method is based on the thermochemical action of the powder pressure generator (PPG-BC) before and after COC chemical treatment with the mixture of solvents and alcohols. It was assumed that powder
gases will create cracks and channels in the bottomhole zone of the well, through which solvents can penetrate.

It should be noted that hydrochloric acid was also used in the compositions. However, the maximum effect was only 0.5-1.0 tons of oil per day for 3 months. Therefore, in the future, this technology was not considered for application at the field.

High reservoir unevenness caused by flooding leads to the formation of groups of active and inactive reserves. Based on the differentiation of technologies application conditions, the deposit was zoned according to the conditions of effective recovery methods. Potential objects (zones, blocks) for different recovery methods were identified [8].

3. Results
Each method has its most effective application. There is no universal technology that allows obtaining high efficiency for the entire spectrum of a real variety of geological and physical factors. Therefore, the most important stage of works within the framework of the considered problem is the choice of the recovery target at the oil field. The recovery target in this case may be a separate well, site or oil deposit as a whole.

Each method has its own applicability criteria, which are caused by the peculiarities of the implemented development process. However, there are criteria common to all methods that determine the effectiveness and feasibility of using methods that increase the oil recovery factor. Such criteria include, for example:

- reservoir-scale fractures, which lead to an advanced breakthrough of pumped expensive agents into production wells and reduces oil recovery and formation coverage;
- high water saturation of the oil formation (more than 65-70%) excludes effective application of most methods for economic reasons, since the costs of preparation and injection of displacement agents are not compensated by additional oil produced. Therefore, there is a need for detailed studies to determine the distribution of oil saturation in the area and section of the deposit, which will allow selecting areas with a sufficiently high oil saturation that ensures the cost effective application of a particular method of oil recovery;
- high oil viscosity (more than 50 mPa·s) excludes effective application of most methods used in flooding. If oil viscosity does not exceed 150-200 mPa·s, then polymer flooding methods can be used. If oil viscosity is more than 200 mPa·s from the point of view of achieving a sufficiently high oil recovery it is advisable to use thermal methods or their combination with other methods of enhanced oil recovery;
- high clay content of the reservoir (clay content – more than 10%) reduces the efficiency of using physicochemical methods due to large adsorption of chemical products and depletion of injected solutions with chemicals. The use of thermal methods in clay formations leads to swelling of clays and a decrease in the permeability of the formation;
- high hardness of reservoir water, and especially water used to prepare solutions of injected reagents, sharply reduces the efficiency of using almost all physical and chemical methods. The efficiency is particularly adversely affected by the high content of calcium and magnesium salts in water due to the formation of precipitates, adsorption of chemicals and a decrease in the displacement ability of solutions.

During polymer flooding, the temperature of the formation should not exceed 80-90°C, since at a higher temperature the polymer is destroyed. With a formation permeability of less than 0.2 μm², the process is difficult to implement, since the sizes of the molecules are larger than the sizes of the pores, which may lead to either colmatation of the bottomhole zone or mechanical destruction of the molecules. Under conditions of increased salinity of water and high content of calcium and magnesium salts, aqueous solutions of polyacrylamide become unstable and their structure is disturbed. Biological polymers remain stable under such conditions [9].

Currently, a gel-forming system based on cross-linked water-soluble PAM with SAA addition is used at Priobskoye field during flooding. The use of the system in the fields of Khanty-Mansiisk autonomous district revealed the following advantages:
selectivity of action on the watered layer;
- controlled gelation;
- stability of the composition over time;
- does not depend on formation temperature and water mineralization.

The technological efficiency of the system based on cross-linked water-soluble PAM with SAA addition taking into account the number of well treatments is shown in Fig. 1.

![Fig. 1. Efficiency of the system based on cross-linked water-soluble PAM with SAA addition.](image)

The system also showed good efficiency at Priobskoye field.

The treatment of the well No. 534 and the recovery results in observation wells are shown in Fig. 2. During operation, 238 m³ was pumped into the well No. 534, for 4 observation wells the additional production amounted to 1,171 tons and stabilized watering, and the last indicator on average allows noticing even a certain decrease [10].

Domestically-made polymer is used: polyacrylamide CSE-1614 (TU 2458-016-66875473-2014).

The polymer system is resistant to high temperatures, high mineralization, and shear stress.

Due to good adsorption on the pore walls, the permeability of the pore channel decreases, thus leading to the redistribution of filtration flows in the formation.

The technology of enhanced oil recovery with the use of the systems implies the injection of a fringe of sewed polyacrylamide solution with multipurpose ML-80 SAA into the layer through injection wells. The principle of operation of the technology consists in plugging of washed pore channels and additional washing of SAA oil from low-permeable interlayers.

The addition of SAA facilitates the injection into a relatively low permeability formation by reducing the resistivity of the formation. The system has selective penetration into a water-saturated part of the productive formation. First, this is caused by a deeper penetration of the composition into the zones of increased permeability due to an increase in the flow resistance of the PAM solution while reducing the permeability of the medium; second, by the fact that the PAM macromolecules are adsorbed on the hydrophilic surfaces of the well-washed watered interlayers, while the hydrophobic pore surface of the oil-saturated part of the formation prevents the physical and chemical interaction of the system with the pore space. This in particular leads to the removal of the gel from the formation by the oil flow. The presence of SAA improves the wettability of the oil reservoir rock, penetrating and oil-displacing ability. The SAA has a plasticizing effect on the gel.
The implementation of the technology results in the following:
- restriction of the penetration of injected water into production wells along highly permeable zones of the formation;
- stabilization or reduction of watering of products of surrounding production wells hydrodynamically connected to injection wells;
- involvement of hard-to-recover oil reserves from zones with reduced permeability;
- increase of oil production in areas of deposits and fields as a whole.

The polymer gel-forming system has the following component ratios: polyacrylamide (PAM) – 0.5-1.5%; ML-80 – 1.0-1.5%; chromium acetate content – 0.01-0.04% (depending on the chromium content in the product), the rest is fresh water.

Polyacrylamide (PAM) is a synthetic high-molecular compound. The most common imported, powdered PAM grades are CS-131, PDA-1041, ORP-40NT, DMP-310, Accotrol-S622 and their analogues with molecular weight above 10 million units, basic substance content – at least 90%, degree of hydrolysis – 5-20%, from which 0.3-1.0% aqueous solutions are prepared [11, 12].

Chromium acetate is used as a crosslinking agent. It represents the combination of a trivalent chrome (Cr(CH₃COO)₃). Chromium acetate is a dark green liquid, the use of which makes it possible to vary the range of gelling times within wide limits. There are two types of this agent in Russia – with chromium mass fraction of 10-12% and 5-7%.

Surface acting agents (SAA) ML-80 (ML-81) – multifunctional composite (nonionic-anionic) summer and winter forms. ML-80 SAAs are produced according to TU 2481-046-04689375-96.

Wells with a sealed production string, a high-quality cement sheath behind the string that excludes behind-the-casing flows, and a serviceable wellhead assembly are selected for the injection of cross-linked PAM systems to the injection well. Well bottomhole must be clean and have a sump of at least 5 m, which allows carrying out the well logging. Field geophysical tests is performed in a well before and after the PAM-based system injection. According to the obtained measurement data, the “water intake – injection pressure” dependence is built.

The existing PAM-based injection instruction recommends the following injection volumes and component concentrations as shown in Table 1.
Table 1. Recommended injection volumes and concentrations of the gelling system components

| Water intake, m³/day | Formation thickness, m | Polymer content, % | Chromium acetate, % | SAA content, % | Polymer injected amount, m³ | Cross linker injected amount, m³ |
|----------------------|------------------------|--------------------|--------------------|----------------|-----------------------------|-------------------------------|
| 750-500              | Up to 20               | 0.7                | 0.02               | 1.5            | 450                         | 50                            |
| 750-500              | 10-15                  | 0.5                | 0.01               | 1.0            | 360                         | 40                            |
| 750-500              | Up to 10               | 0.7                | 0.02               | 1.5            | 270                         | 30                            |
| 500-350              | Up to 20               | 0.5                | 0.02               | 1.5            | 270                         | 30                            |
| 500-350              | 10-15                  | 0.5                | 0.01               | 1.0            | 180                         | 20                            |
| 500-350              | Up to 10               | 0.5                | 0.01               | 1.0            | 135                         | 15                            |

Fig. 3 shows the arrangement and connection of equipment and special machinery during injection.

Fig. 3. Diagram of equipment arrangement during injection: 1 – injection well; 2 – pump unit CA-320M; 3 – AC-10 chemical truck; 4 – formation

4. Conclusion
In recent years, the field has increased the operating water and idle well stock disconnected due to a small oil flow rate and a large amount of produced water, while many of them have not fully developed their reserves. One of the main reasons for these factors is the breakthrough of the injected water through watered high-permeability interlayers. Various methods are used to eliminate this type of water inflow at Priobskoye field. The greatest efficiency is achieved by using a system based on a cross-linked water-soluble PAM with SAA addition. In 2014, using the selected method, 261.36 thousand tons of oil were additionally produced, water cut was reduced in some cases from 85 to 63%.

The analysis showed quite high efficiency of this technology.

References
[1] Mukhametshin V V and Kuleshova L S 2020 On uncertainty level reduction in managing waterflooding of the deposits with hard to extract reserves Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering 331(5) 140–146 DOI 10.18799/24131830/2020/5/2644
[2] Mukhametshin V Sh 2020 Rationale for the production of hard-to-recover deposits in carbonate reservoirs IOP Conf. Ser.: Earth Env. 579 012012 1–5 DOI: 10.1088/1755-1315/579/1/012012
[3] Snow N Tippee B 2013 Optimizing Methods of Exploitation Oil Field Journal Oil&Gas 21 18-21
[4] Schulz H E 2011 Hydrodynamics - Optimizing Methods and Tools (Moscow: InTech.) 420 p
[5] Yakupov R F, Mingulov Sh G and Mingulov I Sh 2020 Production of reserves of oil- water zones of low-viscosity oil deposits IOP: Earth and Environmental Science (EES) (International Symposium «Earth sciences: history, contemporary issues and prospects») 579 012022 DOI 10.1088/1755-1315/579/1/012022

[6] Petrova L V, Yarulli D R 2019 Evaluation of the effect of asphalt resin paraffin deposits on oil well performance IOP Conference Series: Materials Science and Engineering 560 012084 DOI: 10.1088/1757-899X/560/1/012084

[7] Mukhametshin V V and Kuleshova L S 2019 Justification of Low-Productive Oil Deposits Flooding Systems in the Conditions of Limited Information Amount SOCAR Proceedings 2 16–22 DOI: 10.5510/OGP20190200384

[8] Yusupova L F, Almukhametova E M, Nosirov D S, Safiullina A R 2021 Appropriate use of dissolved gas energy in fields at the final stage of development IOP Conference Series: Materials Science and Engineering (International Conference on Mechanical Engineering, Automation and Control Systems (MEACS 2020)) 1064 012074 DOI:10.1088/1757-899X/1064/1/012074

[9] Almukhametova E M, Zakirov A I, Fattakhov D I, Stepanova R R 2019 Simulating Geological Features of Torrential Deposits Advances in Engineering Research (VIII All-Russian Science and Technology Conference “Contemporary Issues of Geology, Geophysics and Geocology of the North Caucasus” (CIGGG 2018)) 182 9-13 DOI: 10.2991/ciggg-18.2019.2

[10] Khlamushkin I K, Garifullina Z A, Gabzalilova A Kh, Khusnutdinova R R 2014 On the issue of calculating the increase in oil production from the implementation of intensification measures Problems of collection, preparation and transportation of oil and oil products 1 (95) 21-25

[11] Gogarty W B, Tosch W C 1968 Miscible-Type Water-flooding: Oil Recovery with Micellar Solutions Journal of Petroleum Technology 243(12) 1407—1414

[12] Moradi F, Rahamanifard H, Schaffie M 2014 The effect of surfactant on performance of polymer systems used during enhanced oil recovery operations Energy Sources. Part A. Recovery, Utilization and Environmental Effects 36(6) 582-590