Enhanced Oil Recovery Technologies for Arctic and Siberian Regions

L K Altunina1,2, V A Kuvshinov1, I V Kuvshinov1, L A Stasieva1

1Institute of Petroleum Chemistry, Siberian Branch of the Russian Academy of Sciences (IPC SB RAS), 4, Akademichesky Avenue, 634055, Tomsk, Russia
2National Research Tomsk State University, 634050 Tomsk, Lenin Avenue, 36

E-mail: alk@ipc.tsc.ru

Abstract. The results of laboratory research, field testing and industrial use of physicochemical and integrated enhanced oil recovery (EOR) technologies for fields of Arctic and Siberian regions are presented. The EOR technologies are based on the concept of using reservoir energy to generate gels, sols and surfactant systems preserving in the reservoir a complex of properties that are optimal for the purposes of oil displacement. The technologies using gel-forming compositions and surfactant-based oil-displacing systems are applicable in extreme climatic conditions, effective in a wide range of geological and physical conditions and stages of field development, cost-effective and environmentally friendly.

1. Introduction

Currently, the development of the natural resources of the Arctic is a priority state task. Its solution is complicated by extreme climatic conditions, which place high demands on the technologies and materials used. In the coming decades, the Arctic region in Russia will be the main reserve of the country's oil and gas industry. For the effective development of oil and gas fields in the Arctic, it is necessary to create and apply large-scale scientifically sound technologies for oil and gas production adapted to northern conditions, to develop new chemicals for implementation of technologies [1-4].

For more than 30 years, IPC SB RAS has been carrying out fundamental and applied studies of natural hydrocarbon systems, on the basis of which new technologies for oil production are created. To intensify the development and improve oil recovery of oil and gas facilities with difficult-to-recover reserves, including deposits of heavy, highly viscous oils, a promising concept has been developed to use the energy of the formation or injected heat carrier to generate chemical “smart” nanoscale systems: gels, sols, solutions of surface-active substances (surfactants) and buffer systems with adjustable alkalinity, preserving, self-sustaining in the formation for a long time a complex of colloidal-chemical properties, optimal for oil displacement [4, 5]. Eleven EOR technologies have been created that are industrially used by the oil companies LUKOIL, ROSNEFT, etc., and 200-300 wells are processed annually. Through their use over the past 5 years, more than 3 million tons of oil have been additionally produced. Industrial production of a number of compositions has been organized.

The accumulated knowledge and scientific and technical experience of the IPC SB RAS were used to adapt the developed technologies and create new technologies for increasing oil recovery using gel-forming and oil-displacing systems for Arctic and Siberian regions, which are applicable in extreme climatic conditions, effective in wide range of geological and physical conditions and stages of field development feasible using standard oilfield equipment. Chemical reagents for performing technologies
are environmentally safe products of large-tonnage commercial production. They have solid commodity form or low freezing point (minus 20 °C to minus 60 °C), and can be delivered by any transport.

2. Oil-displacing systems based on surfactants and buffer systems

Promising for oil fields in Siberian and Arctic regions are technologies for increasing oil recovery, reducing water cut in production wells and intensifying oil production using smart oil-based surfactant compositions with adjustable viscosity and alkalinity: NINKA®, thickened NINKA-Z, GBK and IHN-PRO. The technologies are applicable in difficult operating conditions, including for highly viscous oil fields developed both with the use of thermal methods and without thermal-steam stimulation [4-6].

Since 2003, on the Permian-Carboniferous reservoir of the high-viscosity oil in the Usinsk field, LUKOIL-Komi LLC, together with the IPC SB RAS, LUKOIL-Engineering LLC and OSK LLC, have been conducting field tests of integrated technologies of steam-thermal and physicochemical treatment and industrial use of the developed technologies, as well as “cold” physicochemical technologies to enhance oil recovery and intensify heavy oil production under natural conditions, without heat exposure, using gel-forming and oil-displacing systems [4-6].

Oil-displacing compositions based on the surfactant – carbamide – ammonium salt – water system have been created at the IPC SB RAS, which in the formation at high temperature or due to the thermal energy of the injected heat carrier generate carbon dioxide CO₂ and an alkaline buffer system (NINKA® compositions), which contribute to a decrease in oil viscosity and additional its displacement [4, 5]. In the reservoir, under the influence of high temperature, carbamide is hydrolyzed to form CO₂ and ammonia NH₃. CO₂, unlike ammonia, is much more soluble in oil than in water. Therefore, in the oil – water system, the oil phase will be enriched in CO₂, and the aqueous phase will be enriched in NH₃, which forms an alkaline system with an ammonium salt with a maximum buffer capacity in the pH range of 9 ÷ 10 [5], which is optimal for oil displacement. The dissolution of CO₂ in oil leads to a decrease in its viscosity, Figure 1. CO₂ and NH₃ reduce the swelling of clay minerals of the reservoir rock and thereby contribute to maintaining the initial permeability of the formation. The ammonia buffer system formed during the dissolution of ammonia in an aqueous solution of ammonium salts plays the same role. In addition, due to its alkalinity, pH 9 ÷ 10, and the presence of surfactants, it contributes to the additional displacement of oil, reduction of interfacial tension and degradation, thinning of highly viscous layers or films at the oil – water – rock interfaces, which worsen the filtration of liquids in the reservoir and reduce the completeness of oil production.

On the Permian-Carboniferous reservoir of the Usinsk oil field and on the Gaoshen oil field (China) in 2003-2007 field tests of NINKA® systems were conducted. It was found that their use in stationary steam injection leads to a decrease in water cut by 10-20 % and an increase in oil production by an average of 40 %. Under the cycle-steam stimulation (CSS) with NINKA® systems, an increase in oil production is observed by 1.5-3 times, a decrease in oil viscosity by 2-3 times, Figure 2. Currently, technologies using NINKA® systems are used on an industrial scale, for example, Figure 2.

**Figure 1.** Decreasing oil viscosity of Liaohe field after thermostating during 6 h at 200 °C with NINKA® system.

**Figure 2.** Commercial use of EOR technology in 2017, increase in oil production rate for 37 production wells in Usinsk oil field after the CSS with NINKA® system.
A further development of the work was the creation of compositions, suitable for the Arctic and Siberian regions, with adjustable viscosity and alkalinity, which increase of both the oil displacement coefficient and the coverage coefficient of the formation during water and steam flooding. A thickened oil-displacing composition based on surfactants, ammonium salts, aluminum and carbamide (NINKA-Z) was created, which, as a result of chemical evolution directly in the formation, becomes both a flow-rejecting and oil-displacing composition [4]. As mentioned above, in the formation, at high temperature carbamide is hydrolyzed, forming CO₂ and NH₃, which with an ammonium salt gives an alkaline buffer system. Raising the pH causes hydrolysis of the Al salt to form Al hydroxide sol, while the viscosity of composition increases by 1-2 orders of magnitude. This leads to increase in thermal coverage of the formation, the inclusion of low-permeability layers, decrease in the viscosity of the oil and its washing out. As a result, there is an increase in the coefficient of coverage of the reservoir, an increase in the oil recovery factor (ORF) and the intensification of oil production.

Studies of the kinetics of sol formation and the rheological properties of solutions and sols obtained at 90, 150, and 200 °C showed that after thermostating of sol-forming oil-displacing composition with adjustable viscosity and alkalinity, depending on the concentration of aluminum salt, the viscosity of the composition increases 6-78 times, the pH of the composition after thermostating rises to 7.7-10.1 u. As an example, Figure 3 shows the results of a study of the rheological properties of the composition before and after the formation of the sols due to thermostating at 150 °C for 5 h. The measurements were carried out after cooling the composition to 20 °C. Before thermostating, the composition is a Newtonian fluid, after the formation of the sol, it is a viscoplastic fluid, Figure 3.

Figure 3. The complete rheological flow curves and dependence of NINKA-Z system viscosity before and after 5 h of thermostating at 150 °C: before thermostating system is Newtonian fluid, after the sol formation – viscoplastic fluid.

In 2014-2015 field tests of the composition were carried out, the NINKA-Z thickened composition was pumped into 7 steam injection wells in the pilot site of the steam stimulation on the Permian-Carboniferous reservoir of the Usinsk oil field, Komi Republic (Figure 4). The injection volume was 80-110 m³ per well, the effect was monitored for 75 producing wells of the site. According to the results presented in Figure 4, a steady decrease in water cut and an increase in oil production after injection are seen. The total effect on the site amounted of more than 70 thousand tons of additional oil. The technology is recommended for commercial application.

To enhance oil recovery and intensify the development of high-viscosity oil deposits in the absence of steam stimulation, at 20-40 °C, oil-displacing compositions using surfactants and polyols with controlled viscosity were developed at the IPC SB RAS: alkaline composition IKhN-PRO, based on inorganic buffer system, and acid composition GBK of prolonged action, based on inorganic acid adduct [4, 6]. Compositions have a freezing temperature of minus 20 ÷ minus 60 °C, low interfacial tension at the oil boundary, adjustable density, from 1100 to 1300 kg/m³, and viscosity – from tens to hundreds of
mPa∙s, applicable in the natural mode of development of high-viscosity oil deposits. The GBK composition is most effective in carbonate reservoirs, has a delayed reaction with carbonate rocks, does not form insoluble products, and restores the initial permeability of the reservoir.

In 2014, to increase the production rate of low-productive producing wells of the Permian-Carboniferous reservoir of the Usinsk oil field without steam heat stimulation, the IKhN-PRO composition was injected into 5 and GBK into 10 production wells, Figure 5.

![Figure 5](image)

**Figure 5.** The results of pilot tests in low-yield production wells of the Permian-Carboniferous reservoir of the Usinsk oil field using acid oil-displacing system (as a result of 19 months): a – the increase of the average values of the monthly oil production rate before and after injection; b – increase in oil production and liquid flow rates total for 10 wells.

After injection of the compositions, the oil production rate increased by 5.5-14.8 tons/days and liquid flow rates – by 15-25 m³/day. Incremental oil production amounted to 28 thou tons, 1600-2000 tons/well. The EOR technologies were recommended for commercial application. All components of the systems are environmentally safe products of large-tonnage industrial production. The technologies are applicable for the Arctic and Siberian regions.

### 3. Thermotropic gel-forming systems for enhanced oil recovery and for water shutoff

To enhance/improve oil recovery (EOR/IOR) and limit water inflow to deposits with highly heterogeneous reservoirs, including those in the northern and arctic regions, gel technologies have been created at the IPC SB RAS. They use thermotropic gel-forming systems, which under surface conditions are low-viscosity aqueous solutions, in reservoir ones they turn into gels. Gelation occurs under the influence of thermal energy of the reservoir or the injected heat carrier, without crosslinking agents [4, 5]. The gelation kinetics, rheological and filtration characteristics of various types of gels for heterogeneous formations with permeability in the range from 0.01 to 10 μm² were studied. Thermotropic gel-forming systems are proposed: polymer based on cellulose ethers (CE) and carbamide (METKA®) and inorganic systems “aluminum salt – carbamide – water” (GALKA®) with different time of gelation – from several minutes to several days – in the range temperatures 30-320 °C. Using them, eight gel technologies have been developed to improve oil recovery in highly heterogeneous formations with permeability in the range from 0.01 to 10 μm² were studied. Thermostropic gel-forming systems are proposed: polymer based on cellulose ethers (CE) and carbamide (METKA®) and inorganic systems “aluminum salt – carbamide – water” (GALKA®) with different time of gelation – from several minutes to several days – in the range temperatures 30-320 °C. Using them, eight gel technologies have been developed to improve oil recovery in highly heterogeneous formations that are industrially used in fields in Western Siberia and Komi Republic [4-6]. The environmental safety of reagents and their safety for humans make it possible to widely use gel technology in the fields of Russia and other countries.

The gel-forming ability of thermotropic systems was studied by measuring the viscosity and shear stress using Haake RheoStress 600 rotational viscometer at a temperature of 20 to 150 °C and a pressure of up to 50 atm under dynamic conditions (with full compression). At temperature of 100-150 °C, after a certain time, the solution turns into a solid-like gel of a coagulation structure with pronounced thixotropy and yield strength of 25-90 Pa, Figures 6, 7. The yield strength increases with increasing loading rate. The type of rheological dependences indicates the viscoelastic properties of the gels. It should be noted that in the shear rates range of 0.01-5 s⁻¹ at high pressures, the shear stress and gel viscosity in the systems: aluminum salt – carbamide – water and CE – carbamide – water are several
orders of magnitude higher, figures 6, 7, than at atmospheric pressure [5]. The addition of carbamide and ammonium rhodanide to CE solution leads to increase in gelation temperature, while the effect of the additives is additive: when the carbamide and ammonium rhodanide are combined, the gelation temperature can be higher than 100 °C (Figure 7). The gels are stable and retain their rheological properties at high temperatures – up to 150-200 °C.

Technologies for Arctic and Siberian fields are promising using thermotropic gel-forming systems: inorganic (GALKA®), polymer (METKA®) and systems with two gel-forming components – polymer and inorganic (MEGA), which directly in the reservoir form cohesive nanosized “gel-in-gel” structures with improved rheological characteristics and structural-mechanical properties [4-6].

To improve the effectiveness of the thermal-steam stimulation due to selective water shutoff, in 2014 the METKA® system was injected into 5 production wells in the Usinsk oil field, on the site of the areal steam injection. The volume of the injected system was 19-95 m³ per well. After the injection of the METKA® system one observed the increase in the oil production rate and the decrease in the water cutting of the production wells, Figure 8, a. Incremental oil production was ~ 11,000 tons, or 2,100 tons per well. The treatment was effective for 16 months. Based on the results of the pilot tests, the EOR technology has been recommended for commercial application.

For water shutoff and to enhance oil recovery at reservoir temperatures of 60-220 °C, at water flooding, thermal-steam and cycling-steam stimulations IPC SB RAS has created a high-temperature gel-forming MEGA system with two gel-forming components – polymer and inorganic, based on the "aluminum salt – cellulose ether – carbamide – water". The system generates in situ connected-disperse nano-sized structures of the "gel-in-gel" type with improved rheological characteristics and structurally mechanical properties [4, 6]. The reservoir heat energy or that of the injected heat carrier without a cross-linking agent is a factor causing gelation. When heated above the lower critical temperature of dissolving the cellulose ether, in the system due to a phase transition first a polymer gel is formed and then inside the polymer gel an aluminum hydroxide gel is formed by a mechanism of hydrolytic polycondensation initiated by the products of the carbamide hydrolysis. As a result the structural and mechanical properties of the gel are improved, its viscosity and elasticity multiply increase. The gels formed in reservoir restrain water or steam breakthroughs from injection to production wells and redistribute the filtration fluid flows in reservoir. It stabilizes or decreases water cuttings of the surrounding production or steam-cyclic wells and thereby increases oil production.

The first pilot tests of the EOR technology employing the gel-forming nano-structured MEGA system for water shutoff and to enhance oil recovery were carried out at the end of 2016 at five production wells on the Permian-Carboniferous reservoir in Usinsk field at CSS and on the site of the areal steam injection. The volume of the injected system amounted to 80-120 m³ per well. After well treatment one observed significant decrease in water cut, by 12-40 %, and multiple increase in the oil production rates, Figure 8, b. The pilot test results proved the ability of the MEGA system to block effectively the water inflow into the production well.
In 2015-2018 more than 190 wells have been stimulated on the Permian-Carboniferous reservoir of high-viscosity oil in the Usinsk oil field using the EOR/IOR technologies created at the IPC SB RAS. The additional oil production amounted to more than 900 thousand tons. The use of gels with areal steam stimulation leads to an increase in the coverage of the formation by steam injection, a decrease in water cut by 3-45%, an increase in oil production by 11-33%, and a decrease in liquid production by 14-25%. Under the CSS, the increase in oil production was from 3 to 24 tons per day per well, and additional oil production averaged ≈1,000 tons per well treatment.

4. Conclusions
At the Institute of Petroleum Chemistry SB RAS a promising concept has been developed for using the energy of the formation or injected heat carrier to generate chemical “smart” nanoscale systems directly in the reservoir: gels, sols, surfactant solutions and buffer systems with controlled alkalinity, which preserve and maintain a complex of colloidal chemical properties in the reservoir for a long time optimal for oil displacement. With their application, new physicochemical and integrated technologies have been created to enhanced/improved oil recovery and intensify the development of deposits in the Arctic and Siberian regions, including deposits of highly viscous oils.

The EOR/IOR technologies are applicable in extreme climatic conditions, effective in a wide range of geological and physical conditions and stages of field development, and are carried out using the applied oilfield equipment. Chemical reagents for the implementation of EOR/IOR technologies are environmentally friendly products of large-tonnage industrial production, have a solid commodity form or low freezing temperature (minus 20 ÷ minus 60 °C), are delivered by any means of transport.

The industrial application of new created EOR/IOR technologies will allow for the profitable exploitation of fields in the Arctic and Siberia, and will contribute to the development of the oil industry in these regions.

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