Application of an Oil-Displacing Composition for Increasing Flow Rate of Low Producing High-Viscosity Oil Wells of the Usinskoye Oil Field

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Abstract

The results of a pilot application of a chemical composition for enhanced oil recovery developed at the IPC SB RAS are presented. The EOR-composition was tested in 2014 at the Permian-Carboniferous heavy oil deposit at the Usinskoye oil field. It is very effective for an increase in oil production rate and decrease in water cuttings of well production. In terms of the additionally produced oil, the resulting effect is up to 800 tons per well and its duration is up to 6 months. The application of technologies of low-productivity-well stimulation using the oil-displacing IKhN-PRO system with controlled viscosity and alkalinity is thought to be promising. This composition is proposed for the 'cold' stimulation of high-viscosity oil production as an alternative to thermal methods.

1. Introduction

Being a vital part of the raw material base of the oil industry in virtually all oil-producing countries, the volume of reserves of heavy and high-viscosity oils is several times greater than that of light and low-viscosity oils [1–4]. Therefore, the development of high-viscosity oil deposits is paid more and more attention [5–7]. To date, the average total volume of oil production in the world is close to 500 million tons and the cumulative production exceeds 14 billion tons. Canada and Venezuela dispose the largest reserves of heavy and high-viscous oils and so do the USA, Mexico, Russia, Kuwait, China, Kazakhstan, and other countries [8]. In Russia, the oils with a viscosity of more than 30 mPa·s account for 7–8 billion tons.

Among the existing methods of enhanced oil recovery (EOR), such as injection of miscible/immiscible gases, chemical flooding, and thermal technologies, the method of natural gas injection is of the greatest interest. At the end of the 1990-s, a number of works (e.g., [9]) reported the role of gas injection on oil extraction and laboratory measurements [10]. Currently, the method of natural gas injection is successfully used at high-viscosity oil fields due to its relative cheapness compared to thermal EOR-methods [11, 12].

There are studies [5] where the mechanism of chemical flooding and the impact of added chemicals on the effectiveness of the EOR-method are considered, using two-dimensional models. Thermal and chemical EOR-methods are quite popular in many oil-producing countries having large reserves of high-viscosity oils. The literature reports laboratory and field data on polymer flooding [13] and injections of solutions of emulsifiers. This topic has received much attention, since thermal EOR-methods are not always applicable, in particular, in the oil fields where the productive layer thicknesses are comparatively low [14].

However, thermal methods of oil enhanced recovery are the most common today in the production of highly viscous oils, e.g. steam displacement of residual oil, cyclic steam injection into the reservoir, and steam-assisted gravity drainage. These methods are mainly used in Canada, the USA, Brazil, Venezuela, Russia, and China. Over the recent 40 years, more than 92% from 550 oil recovery enhancement projects worldwide were performed using thermal methods, specifically, those associated with steam injection. It is possible to

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improve the efficiency of thermal steam-treatment by combining it with physical and chemical methods, in particular with the use of oil-displacing and flow-deflecting systems providing an additional oil displacement and increasing the reservoir sweep efficiency [15, 16]. The development of complex methods of combining thermal steam stimulation and physicochemical treatments is at the initial stage. The general trend in these studies shows a growing importance of thermal EOR-methods, especially where they are combined with physicochemical treatment.

New methods and technologies are being intensively developed at the Institute of Petroleum Chemistry (Russia) to enhance oil recovery from high-viscosity oil fields. These are the methods of combined action by water vapor and physical and chemical composition capable of generating freely disperse and bonded disperse systems in the reservoir, which act as intensifiers and regulators of extraction of heavy oil by thermal methods. 11 New commercial technologies have been created to enhance oil recovery and for water shutoff in the deposits with difficult-to-recovery reserves including high-viscosity oil pools [15–19]. A promising concept has been created using reservoir energy or that of the injected heat carrier to generate oil-displacing fluid, gels and sols in situ [15, 17]. Physicochemical fundamentals have been developed to enhance oil recovery using chemical intellectual systems: gel-forming systems and compositions of surface-active substances, preserving for a long time in a reservoir and self-regulating a complex of their properties, being optimal for oil displacement goals [15–20]. To enhance oil recovery from high-viscosity oil pools at a later stage of their development we have developed EOR technology intended to alternate thermal-steam and physicochemical stimulations by means of surfactant-based oil-displacing systems generating CO_2 and alkaline buffer solution in situ [19].

Though effective, steam stimulation is a technologically sophisticated and highly expensive method. It is therefore of interest to develop methods and systems that exclude steam stimulation. In order to enhance oil recovery of low-temperature deposits of high-viscosity oil without applying steam stimulation, the specialists of the Institute of Petroleum Chemistry have developed an IKhN-PRO system.

This paper presents an analysis of the results of a new ‘cold’ EOR-technology using this IKhN-PRO system at the sites of Permian-Carboniferous pool at the Usinskoye oil field, developed in a natural mode without any heat exposure (PJSC ‘Lukoil’, JSC ‘Lukoil-Komi‘).

2. Experimental

The Permo-Carboniferous pool of the Usinskoye oil field is located within the depth range from 1100 to 1500 m. At initial conditions, oil samples from the Permo-Carboniferous pool are characterized by high values of dynamic viscosity of about 710 mPa·s due to the high content of asphalt-resinous components. Permo-Carboniferous deposits have extremely heterogeneous geological structure and their reservoirs are structurally complex: cavernous-porous, fractured-porous, and fractured-cavernous-porous.

The industrial development of the Permo-Carboniferous pool has been maintained since 1977. By now, the pool has been half drilled by a number of controlled directional wells. Its significant part is being developed following the natural water drive. In order to reduce the oil viscosity and to enhance the reservoir oil recovery, an areal steam injection into the steam-stimulated zone has been used since 1992 and a cyclical steam treatment of the producing oil wells has been performed. The current state of the pool development is characterized by a high degree of water cut of the oil produced, while the development of geological oil reserves remains low.

In 2014, pilot tests of using the IKhN-PRO system were carried out within the Permo-Carboniferous pool of the Usinskoye oil field. Five wells (Nos. 3415, 3420, 527, 3418, and 3421) were treated with this composition, 25–45 m^3 per well. The slugs of diluted and concentrated compositions were alternatively injected into the wells. For each slug, the time of the bottom zone exposure was 12 h. After the injection, the well was blocked and left for 8–19 days, then it was reactivated and production was conducted in the usual manner. Such a bottomhole zone treatment (BZT) is, from an engineering point of view, an analogue of the cyclic steam treatment, the so-called cyclic treatment with reagents, where the additional oil production is achieved due to a physicochemical impact of the injected composition, the cold water being a carrier, rather than a thermal impact of steam.

Alkaline oil-displacing system IKhN-PRO contains surfactants, inorganic buffer solution and polyol with regulated viscosity and alkalinity.

The IKhN-PRO system under study is characterized by:

- low interfacial tension at the boundary with oil and high oil-displacing and oil-flushing capacities;
- variable viscosity in the range from unity to hundreds mPa·s;
- compatibility with saline formation waters and the absence of precipitation upon dilution;

• ability of reducing swelling of reservoir clay minerals and restoring rock permeability;

• applicability in a wide temperature range – from 10 to 130 °C, in sandstone and carbonate reservoirs under different geological and physical conditions;

• low pour point (-20 to -60 °C), which allows production to be performed to work in the northern areas including the arctic oil fields in winter.

Samples of the reservoir water and extracted oil were taken 1–2 months after the treatment. The oil density was determined via the pycnometric method. The viscosities of the oils under study were measured by vibration viscometry using a Reokinetika device.

Microbiological analysis of samples consisted in determination of the bacteria count in the carbon and nitrogen cycles.

Investigation of the composition of oil from the wells before and after treatment with the IkHN-PRO system was carried out by electron spectroscopy and gas chromatography-mass spectrometry (GC-MS) in a Thermo Scientific DFS magnetic chromatography-mass spectrometer (Germany).

The chromatograph was equipped with a Thermo Scientific quartz capillary column (30 m × 0.25 mm i.d. × 0.25 μm film thickness). The stationary phase was TR-5MS, and the carrier gas was helium. The GC oven temperature program was 80 °C (initial hold time 2 min), then 4 °C/min to 300 °C (initial hold time 30 min). The MS analysis was performed via electron impact ionization with the energy of ionizing electrons 70 eV. The temperature in the ionization chamber and that of interface was 270 °C.

The chromatograms for organic compounds were obtained in two ways: from areas of the chromatographic peaks corresponding to the total ion current (TIC) and from the areas recorded for the main ion mass (*m/z*) in a SIM (Single Ion Monitoring) acquisition mode. The individual HCs were identified using a computer search from among the literature data in the library of the National Institute of Standards NIST-05 and by the structure reconstruction according to the character of ionic fragmentation under electron impact. The content of a component was determined by the area of the corresponding peaks on the chromatograms using an internal standard – $C_{12}D_{10}$ deyteroacenaphthene [21].

The spectra from metal porphyrin complexes were registered in a chloroform solution in the visible region in the absorption mode using a Carl Zeiss Jena Specord UV-Vis spectrophotometer (Germany) with an automatic spectrum registration.

3. Results and discussion

The action of compositions used for oil recovery enhancement could be determined not only by an increase in well flow rates, but also by changes in the composition and properties of reservoir water and produced oil. In addition, the composition of the oil produced allows determining the main development object from which it comes into any well, since the Permo-Carboniferous pool of the Usinskoye oil field consists of hydrodynamically interconnected development objects (upper, middle, and lower). This is evidenced by the previous studies of oil compositions of every development object of the Usinskoye oil field. They demonstrated a number of characteristic features of the group and individual compositions of the oils from each development object. The oil samples from the upper development object are characterized by a high content of alkanes, while in the oils from the middle and lower development objects, where aromatic hydrocarbons (HC) predominate, their content is smaller. The alkanes of lower and middle development objects often contain the maximum quantity of C_{16} homolog (so far there is no data on which of the interlayers contain oil of this "anomalous" composition of alkanes), while there is no pronounced maximum in the molecular weight distribution of n-alkanes of the oils from the upper development object. Most oils from the lower development object differ from those of the middle development object by a higher total content of metal porphyrins and a reduced content of phenanthrenes, and the oils of middle development object – by an increased nickel porphyrins – to – vanadyl porphyrins ratio (Table 1).

Additional data could be provided by a physicochemical analysis of the produced oil and aquifer, since the changes in mineralization, cation and anion structure and the variations in pH and Eh would allow controlling both the movement of the composition pumped into the formation (via detection of the substances – components of the composition), and the variations in the fluid flow (e.g., a sudden change in the composition of water after injection); an increased water viscosity indicates that either the polymer components of the composition have dissolved in it or emulsions have formed.

A study of the diversity of the formation microflora may be of scientific and practical interest. The microflora of oil fields stimulates biodegradation of hydrocarbons to form compounds causing additional displacement of oil from the reservoir rock, such as: CO_2, organic acids, alcohols, aldehydes, biological surfactants and biopolymers. This might be used in the development of an EOR biotechnology [22].

Table 1

Content of metal porphyrins in the produced oil before and after the treatment with the IKhN-PRO system

Number of the well	Treatment of the well	Object of the development	Content, nM/g		
			Ni-p	V-p	Ni-p+V-p
527	Before treatment	-	72	233.4	305.4
	After treatment		70.6	233.4	304
3418	Before treatment	Lowel	69	262.6	331.6
	After treatment		70.7	276.9	347.6
3421	Before treatment	Middle	24.9	289.1	314
	After treatment		19.8	190.8	210.6
3415	Before treatment	Lowel + Middle	25.7	252.2	277.9
	After treatment		22.9	218.1	241

A series of microbiological investigations of the oils from the Usinskoye deposit revealed a significant content of heterotrophic microflora in some of the wells of the upper and middle development objects, whose count varied from 0.25 thousand to 1.8 million cell/cm^3. In the samples from the lower development object, the count of microorganisms did not exceed a few tens of cells, the predominating genera being *Rhodococcus*, *Bacillus*, *Actinomyces*, *Pseudomonas*, and *Micrococcus*. In general, the reservoir flora of the Usinskoye oil field is quite varied, but scarce, which could be caused by a low water exchange and the absence of nitrogen nutrition. A microbiological analysis of the reservoir fluids showed minor fluctuations in the count of heterotrophic microflora: 0-$0.9 \cdot 10^3$ CFU/cm^3. In addition, a small amount of denitrifying microorganisms (25–95 CFU/cm^3) was detected in the water from wells Nos. 3415 and 3420.

For all wells, the maximum oil production rates were achieved in about a month after treatment. In the majority of oil samples, they remained at this level for quite a long time – up to 6 months.

The oil extracted from well 3421 located in the south-eastern region of the Usinskoye oil field, which produces oil from the middle development object, was characterized by a hydrocarbon group composition typical for the middle development object of the eastern part of the oil field (Fig. 1).

As a result of injection of the IKhN-PRO system, oil production has dramatically increased (Fig. 2). In 20 days after the treatment, the relative number of alkanes increased, while that of aromatic hydrocarbons decreased and so did the content of C_{16} hydrocarbons (Fig. 1). Thus, the composition of alkanes changed. It might have been caused by an involvement of oil from the overlying reservoirs beds into production, which is similar to that of the upper development object. This is also supported by a four-fold reduction in oil viscosity from 8365 to 1622 mP·s at the time of the analysis.

The oil from Nos. 3418 and 342, located in the south-east and pumping oil from the middle and lower objects, in early August (before injection of the system) was characterized by a lower content of alkanes (Fig. 3) and a higher content of metalloporphyrins in contrast to the oil from the middle object from No. 3421 (Table 1). This is consistent with the presence of oil from both the middle and bottom objects in the well production.

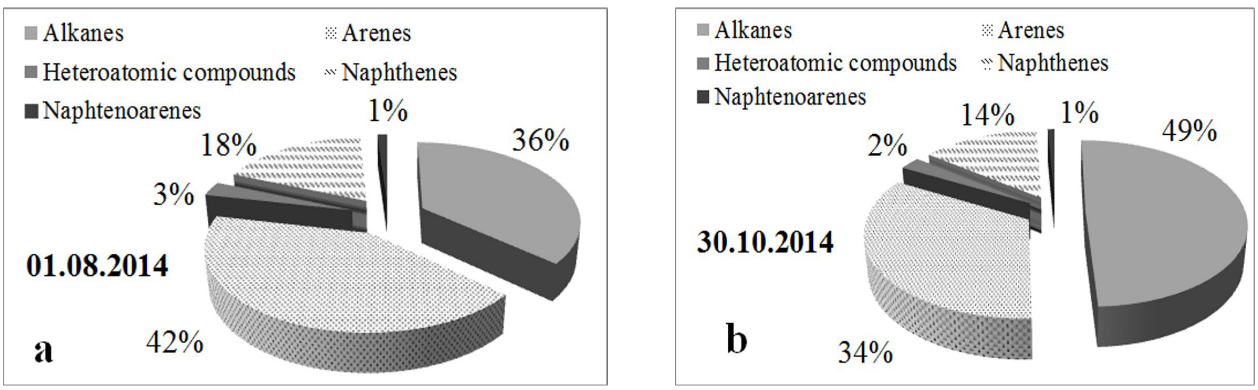

Fig. 1. Group composition of the oil extracted from the well No. 3421 before (a) and (b) after the treatment with the IKhN-PRO system.

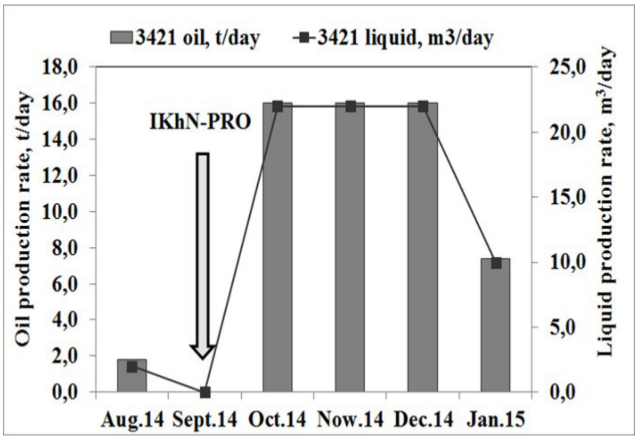

Fig. 2. Oil and liquid production rates for the well No. 3421 after the treatment of bottomhole zone with the oil-displacing IKhN-PRO system.

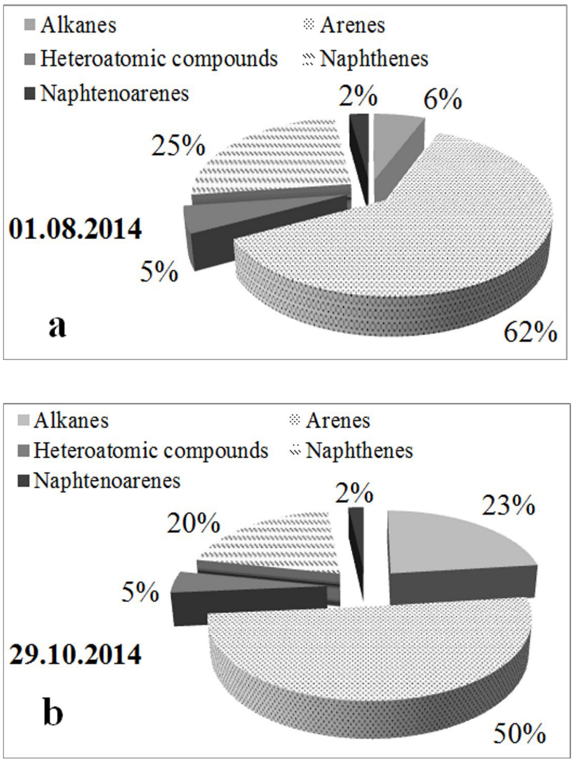

Fig. 3. Variations in the composition of the oil extracted from No. 3418 before (a) and after (b) treatment with the IKhN-PRO system.

Six weeks after the treatment with the IKhN-PRO system, the fraction of alkanes in the oil sharply increased as the oil production from this well was increasing (Fig. 4). Such a change in the composition might have been be due to the increased contribution from the middle object, which indicates a predominating influence of the injected system on the middle object. Furthermore, this is supported by a 36% decrease in oil viscosity (from 9501 to 6105 mPa·s).

The absence of the dominating C_{16} homolog among the alkanes in the oil samples before and after their treatment with the system indicates the presence of other oil saturated interlayers in the middle development object from which the oil came rather than those in well 3421.

The oil sample from Nos. 3415, 3418 and 3421 located in the same region of the deposit, which produce oil from the middle and lower objects, was characterized by a low content of alkanes and a high content of aromatic hydrocarbons before injection of the IKhN-PRO system, which is characteristic of oils from the lower object. Injection of the system caused little if any changes in the group composition of hydrocarbons, registered in late October 2014, when the well production rate decreased after the sharp increase (Fig. 5). The only difference observed is the change in the individual composition of alkanes, including a dramatically increased relative content of the C_{16} homolog, which indicates an increased involvement of the oil from the reservoir with 'anomalous' oil in the oil well production. The oil viscosity has also slightly changed from 7151 to 8119 MPa·s.

The oil, extracted from No. 527 located in the north of the oil field, is similar in its group composition of hydrocarbons to that from No. 3415. It is also characterized by a low concentration of alkanes (11%) and high content of arenes (61%).

Despite the sharp increase in oil production after injection of the IKhN-PRO system (Fig. 6), the group composition of oil hydrocarbons changed only slightly, but C_{16} became predominant. This indicates an additional involvement of the interlayer, presumably, of the lower object into oil production (since the total relative content of alkanes in the oil is somewhat lower), which gave rise to an increase in the oil production.

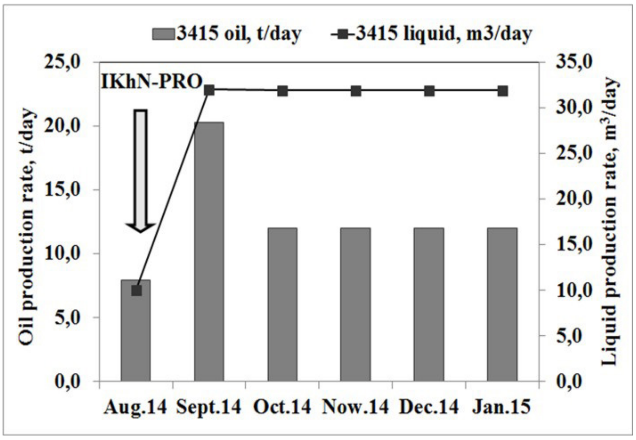

Fig. 4. Oil and liquid production rates for No. 3418 after treatment of the bottomhole zone with the oil-displacing IKhN-PRO system.

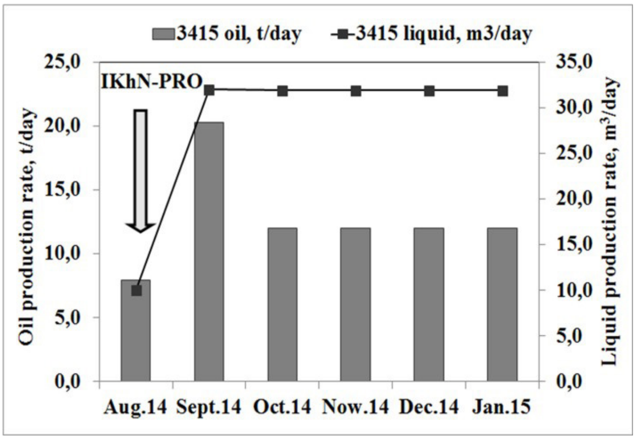

Fig. 5. Oil and liquid production rates for well 3415 after treatment of the bottomhole zone with the oil-displacing IKhN-PRO system.

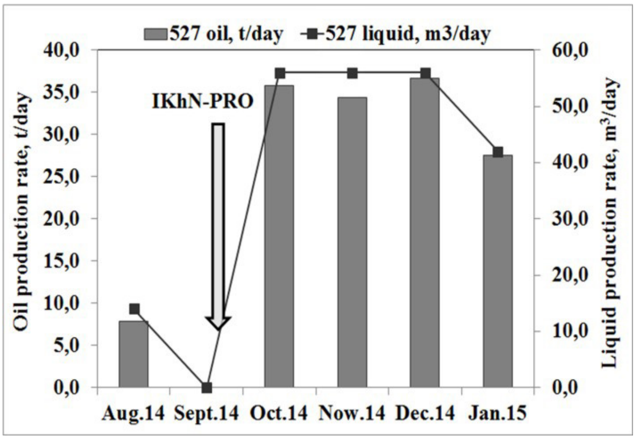

Fig. 6. Oil and liquid production rates for No. 527 after treatment of the bottomhole zone with the oil-displacing IKhN-PRO system.

The oil viscosity, in contrast, has doubled, from 4977 to 8475 mPa·s. Probably the reserve emulsion was formed in the presence of surface-active substances in the system IKhN-PRO, that was accompanied with the increase in the viscosity of the produced oil for wells No 3415 and 527.

A treatment of No. 3420 had a positive effect on the oil production rate: an increased oil production had been observed during 4 months after the injection (Fig. 7). So far, it is impossible to draw any conclusions concerning the changes of fluid flows in the reservoir, since there are neither samples of the formation water nor those of the initial untreated oil.

The density of oils extracted from the same wells before and after treatment did not change at all or changed but only slightly.

The content of carbamide and ammonium ion determined in water after injection of the IKhN-PRO system was found to be 4.500 mg/dm^3 and 1900 mg/dm^3, respectively, which directly testifies of the presence of the system in the producing oil wells.

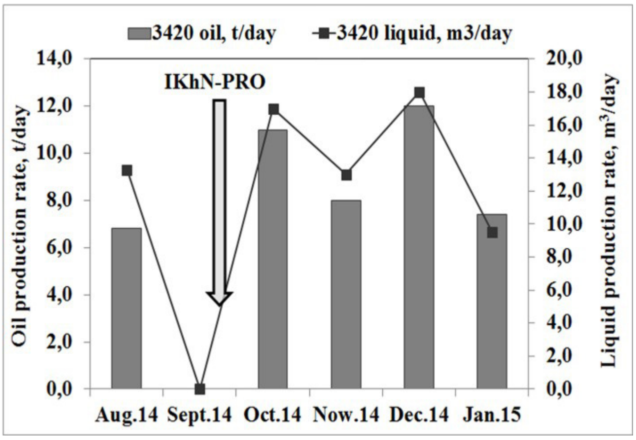

Fig. 7. Oil and liquid production rates for the well 3418 after the treatment of bottomhole zone with the oil-displacing IKhN-PRO system.

Microbiological analysis of the formation fluids after the stimulation with the system demonstrated the growth of the number of heterotrophic microflora: from 0–0.9·10^3 CFU/ml to 50–200·10^3 CFU/ml in 3–4 months after the stimulation due to injection of mineral nitrogen compounds constituting the system into the reservoir.

In general, an additional oil produced for a half-year observation period using the IKhN-PRO system was about 4 000 tons from 5 wells, i.e. about 800 ton/well.

4. Conclusions

After treatment with the IKhN-PRO system, an increase in oil and liquid production rates was observed in all the wells under study. The duration of this effect was as long as 6 months. The amount of additional extracted oil was about 800 tons per one treated well.

The IKhN-PRO system has been proved to be an oil-displacing and flow deviating composition, which follows from the analysis of the changes in the oil group composition, its viscosity and the content of metal porphyrins in this oil. The water samples from Nos. 3415, 3418, and 3420 in the first and second months after treatment contained components of the system (ammonium ions and urea).

The increased number of microflora after the stimulation as a result of the system injection somehow enhanced oil recovery due to metabolism products of the microorganisms.

This system is proposed for the 'cold' intensification of high-viscosity oil recovery as an alternative to the available thermal methods. Large-scale industrial application of the new complex EOR-technologies could extend profitable exploitation of the deposits in the later stage of development and to engage the deposits with hard recoverable hydrocarbon reserves into production, including high-viscosity oil deposits.

The results of the work performed in 2014 indicate that the IKhN-PRO system designed for treatment of the bottomhole zone of low- productivity wells could be recommended for industrial use.

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