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Expanding the experience of using non-stationary waterflooding technology with changing direction of the filtration flow in the example of the Northern Buzachi field

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Abstract. The last few years, work has been carried out to study the effectiveness of non-stationary exposure in the highly viscous oil field Northern Buzachi (Republic of Kazakhstan). It has been proved that this technology is quite effective in the development of highly viscous oil reservoirs, however, in order to constantly maintain high technological effect, a constant modification of this technology is required, since it has a characteristic feature of rapid «aging». Further search for the conditions of effective application of non-stationary exposure on highly-viscous oil deposits can be carried out in two directions: the implementation of non-stationary exposure in new areas with other reservoir parameters and the change in the parameters of non-stationary exposure technology (including combining with other technologies) in areas where this technology is already in use. Both approaches are used on the Northern Buzachi field. Thus, the positive experience of using non-stationary waterflooding in combination with changing direction of the filtration flow in the section of the seventh block of the Northern Buzachi field allowed us to recommend new sites for the implementation of this technology. With the participation of the author of this work, a non-stationary waterflooding program was developed and implemented on the site of the sixth block (south) of the first operational facility.

Keywords: hydrodynamic connection, carbonate, terrigenous reservoirs, erosion incisions, oil recovery coefficient, indicator studies, fluorescein, filtration current lines

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In order to maintain a constant high technological effect from the use of non-stationary technology in the Northern Buzachi (Republic of Kazakhstan) high-viscosity oil field, it is rationally to combine it with other technologies (Ogandzhanyants, 1969; Zhang et al., 2010; Zhdanov et al., 1996).

Let us consider the experience of using the technology of non-stationary exposure in combination with the MDFF (modifying directions of filtration flows) technology in the section of the sixth block (the southern part of the first operational facility).

The main geological and physical characteristics of the first operational site of the Northern Buzachi field (the Jurassic horizons Yu_1 and Yu_2) are presented in Table 1. The main distinguishing features of the geological structure of the deposit are high average permeability of the reservoir, high layered heterogeneity of the permeability field, high viscosity of the reservoir oil.

The structure of oil reserves of Jurassic deposits in the area of the NE (non-stationary exposure) site (Fig. 1) of the sixth block, Northern Buzachi field is shown in Fig. 2. Structuring of the reserves is carried out according to the following main indicators: permeability, layered heterogeneity, zonal heterogeneity of the reservoir, reservoir type, clay index. The intervals of the change in indices, dividing the investigated values into groups, were determined on the basis of the statistical distributions of the parameters of the reservoir properties. During the analysis of the geological structure features of oil deposits in the Northern Buzachi horizons (Nauchno-tekhnicheskoe soprovozhdenie razrabotki mestorozhdeniya Severnye Buzachi, 2014), it was established that the main parameters determining possible complications in the field development are the presence of extensive contact water-oil zones, high layer heterogeneity of permeability properties of the reservoir, zone heterogeneity of permeability. Therefore, the study of oil reserves distribution by these parameters is of particular interest (Almukhametova, 2016).

Parameters	I object
Average depth of occurrence, m	470
Gas and oil contact, m	428-436
Type of deposit	bedded roof fault-bounded
Type of reservoir	terrigenously-porous
Average total thickness, m	47.6
Average net oil thickness, m	20.8
Average net gas thickness, m	4.6
Average porosity, un.fr.	0.34
Average permeability, mkm^2	2.43
Initial oil saturation coefficient, un.fr.	0.73
Sandiness coefficient, un.fr.	0.42
Compartmentalization coefficient, un.fr.	5.9
Initial reservoir temperature, ^0C	29.7
Initial reservoir pressure, MPa	5.8
Viscosity of oil in reservoir conditions, mPa*s	380
Density of oil in reservoir conditions, t/m^3	0.92
Formation volume factor, un.fr.	1.029
Initial (current) saturation pressure, MPa	3.97 (2.29)
Initial (current) gas content, m^3/t	11.8 (7.39)
Viscosity of water in reservoir conditions, mPa*s	1.05
Density of water in reservoir conditions, t/m^3	1.04

Table 1. Basic geological and physical characteristics of the first operational facility of the Northern Buzachi field

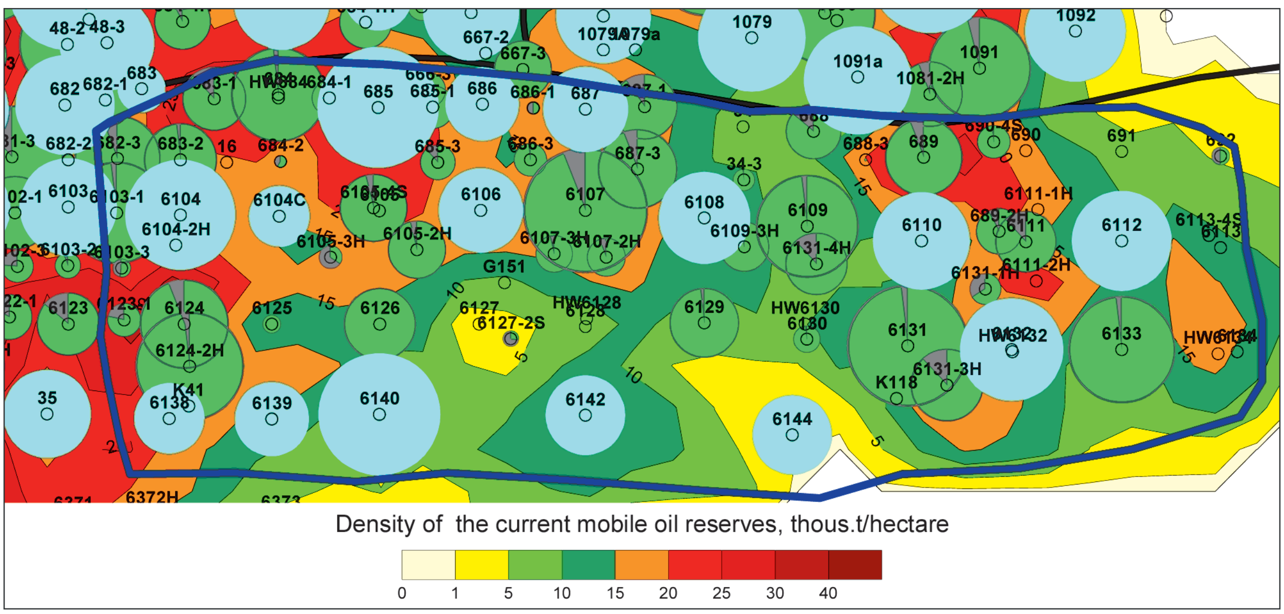

Fig. 1. The map fragment of the current mobile oil reserves of the first operational facility. The area of the non-stationary flooding of Block No. 6. The blue line indicates the contour of the NE site.

Figure 2a shows that for reservoirs of the Jurassic sediments, more than 71% of the oil reserves of the site are concentrated in reservoirs with a high and ultra-high average permeability in the section. In low-permeability zones there is an insignificant share of reserves (2%). The site is fairly homogeneous in permeability along lateral. The overwhelming share of oil reserves (70%) is located in the reservoirs with a small zone heterogeneity of the permeability field (Fig. 2b). A wide spread of average permeability values is accompanied by high (and even super high) values of layered heterogeneity of permeability properties of the reservoir. A significant part of the geological reserves of oil is located in the reservoirs, the permeability of which differ by tens and hundreds of times (55%). 44% of all geologic oil reserves of the facility are concentrated in relatively homogeneous reservoirs (Fig. 2c). The distribution of oil reserves according to the clay index of the reservoir shows that a significant part (43%) of the oil reserves is located in clay reservoirs (more than 20%) (Fig. 2d). This fact brings to the forefront the problem of changing the reservoir properties when it is flooded (Almukhametova, 2016).

Calculations show that when the ultimate water cut is reached, up to 26.2% of all geological reserves and 25.1% of all the mobile oil reserves of the Jurassic deposits of the site remain in the undeveloped reservoir intervals (Almukhametova, 2016). Therefore, the use of

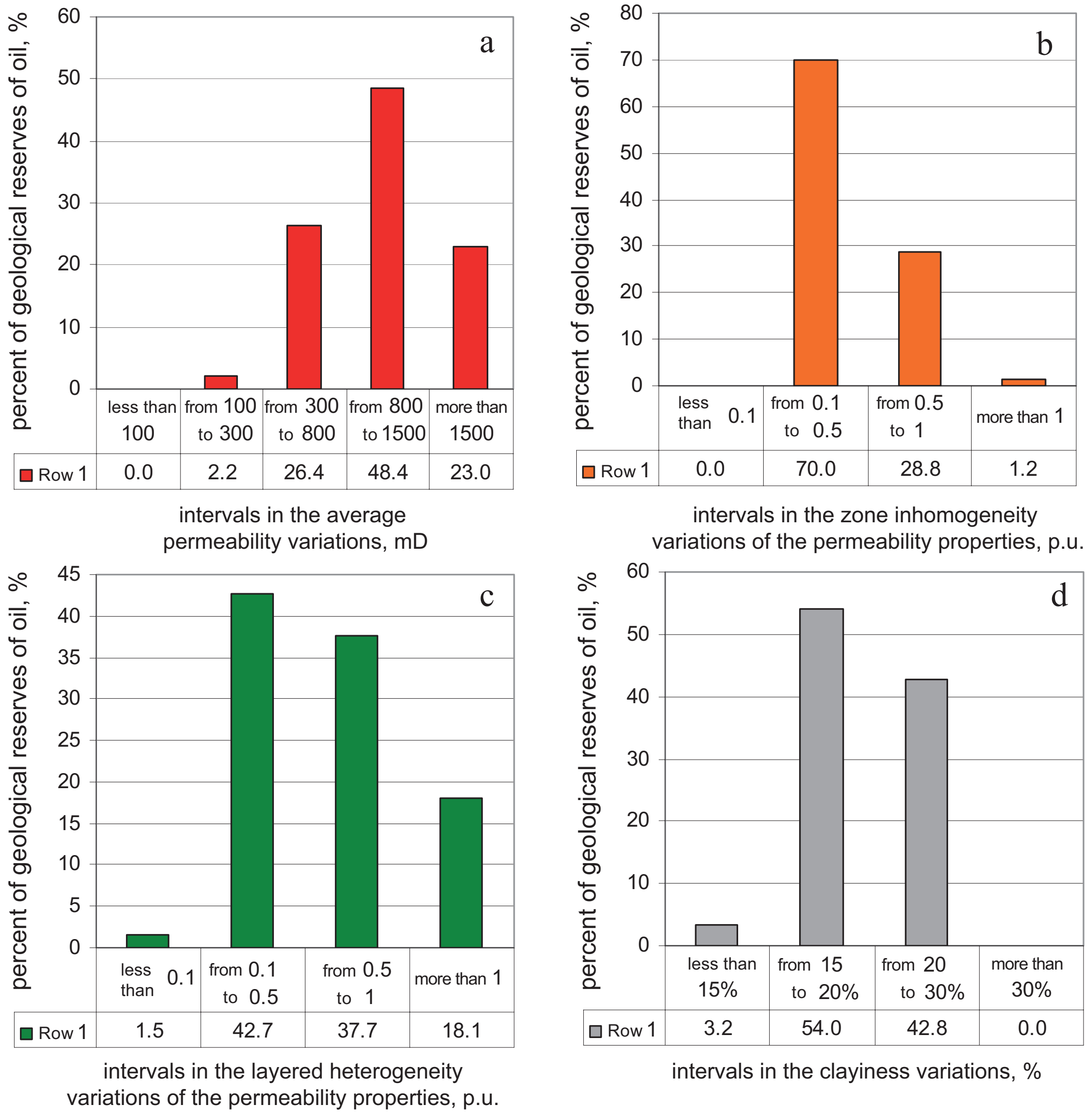

Fig. 2. Distribution of the initial geological reserves of oil in the Jurassic deposits in the area of the NE section of the sixth block along the intervals in the average permeability variations of the reservoir (a), the zone inhomogeneity of the permeability properties of the reservoir (b), layered heterogeneity of the permeability properties of the reservoir (c), clayiness (d) (according to the data (Almukhametova, 2016)).

technologies allowing to connect to active drainage the oil reserves concentrated in the low permeable layers of the reservoir is extremely relevant for the development of the sixth block of the Northern Buzachi field.

Let us consider the dynamics of technological indicators of site development. Figure 3 shows the dynamics of the average monthly production rate and watercut of production in recent years. It can be seen that in recent years (up to 04.2014 –the beginning of the application of NE), the dynamics of the average monthly oil production is characterized by significant fluctuations in its magnitude, which is due to geological and technical measures being carried out at the site. The watercut of the production is slowly increasing. The current compensation for liquid withdrawals by water injection as of 04.2013 was 87%, accumulated compensation – 65%.

Analysis of the production of oil reserves from the first production facility of the NE section of the sixth block shows that as of 01.03.2014 the current oil recovery factor was 0.114 unit shares.

At the same time, the current water cut in the whole area (Jurassic) is 90.8%, the extraction from approved initial recoverable reserves is 35%.

In April 2014, the application of NE technology in combination with the technology of changing the direction of the filtration flow was started at the site. According to the program for the introduction of non-stationary waterflooding in the section 13, exposing injection wells were divided into the northern and southern rows (Scientific and technical support for the development of the Northern Buzachi field, 2014). The northern row includes wells Nos. 685, 6104, 6104C, 6106, 6108, 6110, 6112, the southern row – 6132, 6138, 6139, 6140, 6142, 6144. Groups of injection wells operate in antiphase, i.e. when the wells of the northern row are pumping, the injection wells of the southern row are idle, and vice versa.

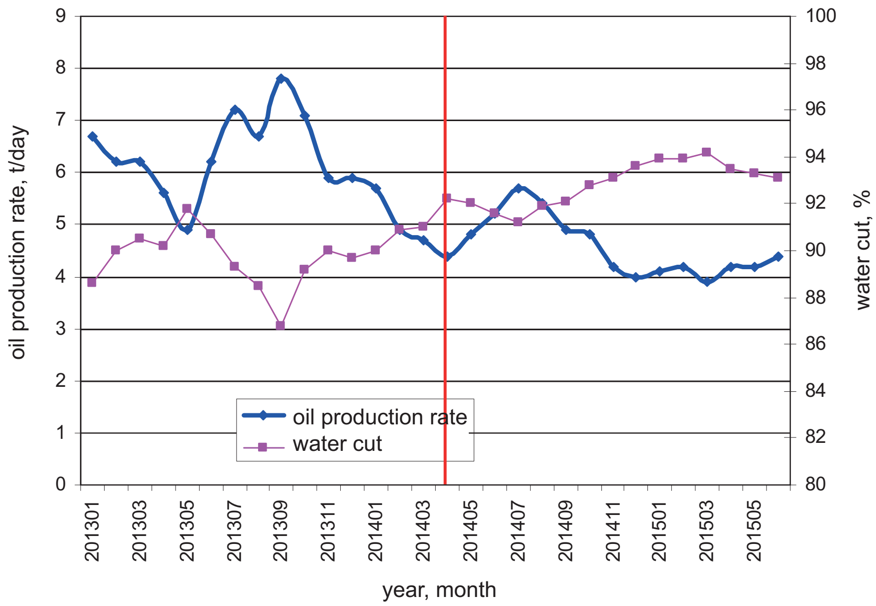

Fig. 3. Dynamics of the average monthly oil production and water cut of the southern section of the sixth block (section NE) in recent years. The first operational site of the Northern Buzachi field

The duration of the half-life of the operation/shutdown groups of the injection wells was determined from the hydrodynamic studies of the injection wells (the pressure drop curve method). Based on the piezoconductivity values obtained and the average distances between the injection and production wells, the mean time of propagation of the pressure change was determined, which was taken as the half-cycle duration. The duration of half-periods of operation/shutdown of injection wells in this area was 6 days.

According to the historical data of the operation of injection wells, the possibility of increasing their injectivity was established, and the operating modes of the water supply system of the reservoir pressure maintenance system of the section were determined during periodic operation of groups of injection wells (Vladimirov, Veliev, Almukhametova, 2014). Due to the fact that all injection wells of the site are supplied with water from a group of water intake wells, regulation of the volumes of injected water during non-stationary flooding was not difficult.

In addition, regimes of non-stationary water flooding were developed in the summer and winter periods of the year. In summer, non-stationary water flooding was applied with the shutdown of groups of injection wells, in winter – with periodic restriction of water injection into groups of wells. In order to avoid complications in the work of reservoir pressure maintenance wells in the winter, the minimum values of the injectivity were established for injection wells, at which the water did not freeze in the water ducts. These injectivity values were taken as the lower threshold for the values of the daily water injection at NE in winter.

The non-stationary water flooding in the area under consideration was started from the stop of the injection wells of the northern row by 5 days. Later, the duration of the half-period varied from 5 to 7 days (Fig. 4). Symmetric cycles with the downtime of injection wells equal to the time of their operation were used.

All 45 production wells were considered as reacting production wells.

By the beginning of the implementation of non-stationary waterflooding technology (04.2014), the dynamics of indicators was characterized by a decrease in oil production with increasing water cut in production. At the beginning of the NE, the average monthly water cut was 92.2%, the average monthly oil production decreased to 4.4 tons per day with a flow rate of 56 tons per day. Average monthly injectivity was 120 m^3/day.

Let us consider the change in technological indicators as a result of applying the technology of non-stationary impact. Figure 3 shows that the beginning of non-stationary waterflooding with the use of technology to change the direction of filtration flows is accompanied

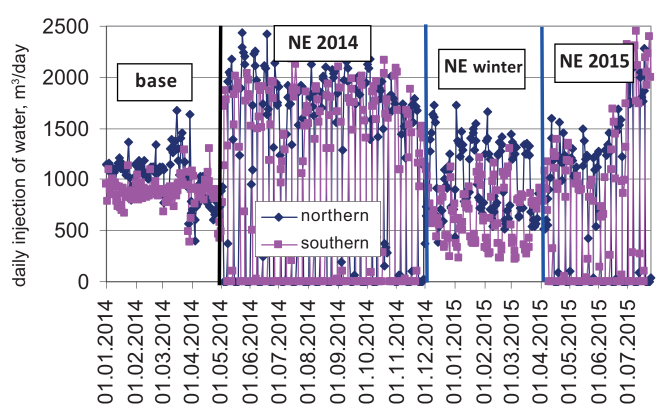

Fig. 4. Cyclical switching on and switching off of series of injection wells in the southern section of the sixth block (the first operational facility). Dynamics of daily injection of injection wells

by an increase in the average oil production rate and a decrease in water cut of the products. However, starting from August 2014, there is a tendency to increase watercut production and reduce oil production. It would seem that the effect of using the technology is over. However, as the comparison of the rate of decline in oil production shows, during the non-stationary waterflooding period 08.2014-12.2014 the rate of decline in oil production is less intensive.

The non-stationary waterflooding on the site in question was carried out continuously during 2014-2015. In winter, the periodicity of the exposure was carried out by limiting the injection along the rows of injection wells (Vladimirov et al., 2014; Khalimov et al., 2014). When switching to the winter regime of non-stationary flooding technology with a change in the direction of the filtration flow, stabilization of oil production and water cut is observed (Vladimirov et al., 2016). With the onset of non-stationary injection in 2015 with shutdown of the series of injection wells, there was a slight decrease in water cut and an increase in oil production.

Thus, non-stationary water flooding at the site allows reducing the rate of decline in oil production and the growth of water-cut production.

Calculation of the efficiency of the applied NE technology was carried out on the basis of displacement characteristics. During the base period, the period of stationary injection on the site was taken. The results of calculating the technological efficiency of NE in combination with the MDFF are presented in Table 2. It should be noted that the magnitude of the effect differs greatly for different displacement characteristics from 3.076 to 10.343 thousand tons. The final value of the effect from the technology of non-stationary water flooding is taken as the average value obtained for the five best displacement characteristics. Evaluation of the effect as of 01.07.2015 showed that the effect of using the technology of non-stationary water flooding amounted to 7.230 tons of additional oil produced.

Let us note some features of the NE use in this area. The first – there are wells of the main and fill-in stocks on the site. The wells of the fill-in stock were drilled at a time when some of the production wells of the main stock were already working with a sufficiently high water cut of the production. In this case, the wells of the fill-in stock were located at smaller distances from the injection wells than the wells of the main stock. Therefore, the problem arises of estimating the technological effect of NE + MDFF by categories of wells.

As a result of the effectiveness analysis of the applied technology of non-stationary exposure on the wells of the main and fill-in stocks, it was found that the maximum specific effect falls on the wells of the fill-in stock (Table 3, Fig. 5a). In general, for

Characteristics of displacement	Technological effect size, t	Duration of effect, month	Theil Index, relat. un.
Qo(1/Ql)	10343	14	3.12E-04
lgQw/Qo(lgQw)	3076	6	3.28E-04
Qo(1/SQR(Ql)	10257	14	3.72E-04
Ql /Qo(Qw)	7213	14	4.06E-04
Qo(lgQw)	5260	14	4.30E-04
Average for the three best	7230	12.4	

Table 2. The technological effect of the application of NE + MDFF on the section of the 6th block (south) of the first operational facility in 2014-2015 (Almukhametova, 2016)

the analyzed period, the specific effect on the wells of the main stock was 325 tons/ well (23 tons / (well month)), the fill-in stock – 563 tons/well (40 tons / (well month)) (Almukhametova, 2016). Thus, the difference in efficiency of the non-stationary waterflooding on the wells of the fill-in and main stocks is significant. The higher effect of NE + MDFF on the wells of the fill-in stock is due to two reasons: the first is the higher amplitude of non-stationary exposure (the well is closer to the source of exposure), the second is less the degree of high-permeability channel production (shorter work time), which increases the efficiency of changing the direction of filtration flows.

The second feature is the use by the subsoil user at the NE site of changes in the operating modes of production wells (optimization). In this case, optimization of operating modes of production wells was mainly aimed at increasing liquid flow rates. In the period of non-stationary flooding, optimization of operating modes of production wells in more than 58% of the well stock of the site was carried out at the site.

Evaluation of the effect of the joint application of optimization technology and non-stationary waterflooding showed that the specific effect was 1.5 times lower in wells where the complex effect (NE + optimization) was applied in comparison with the wells that were located only in the zone of non-stationary water flooding (Table 4, Fig. 5b).

Decrease in the efficiency of NE + MDFF technology in wells with optimization is associated with a sharp increase in water cut in these wells and an increase in liquid production (disproportionate to the change in phase fractions in the flow). On the displacement characteristics, this measure is reflected as a deterioration in the quality of oil displacement, although in some cases there was an increase in daily oil sampling with increasing water cut.

Conclusions

The North Buzachi high-viscosity oil field has become a testing ground for the application of non-stationary water flooding technology. It is well known that waterflooding on deposits of high-viscosity oil is of low efficiency because of the high difference in mobility

Fund	Main	Fill-in	Total
Number of wells, pcs	11	22	33
Cumulative effect, t	3572	12384	15956
Specific effect, t/well	324.7	562.9	483.5

Table 3. Distribution of the effect of NE on the wells of the main and fill-in stocks

Type of geological and technical measures	Cumulative effect, t	Number of wells, pcs	Specific effect, t/well	Percent of failed wells in a group, un.fr.
optimization+ NE	8380	21	399.0	0.24
NE	7576	12	631.3	0.08

Table 4. Distribution of the effect of NE + MDFF on wells with the use of optimization and without it

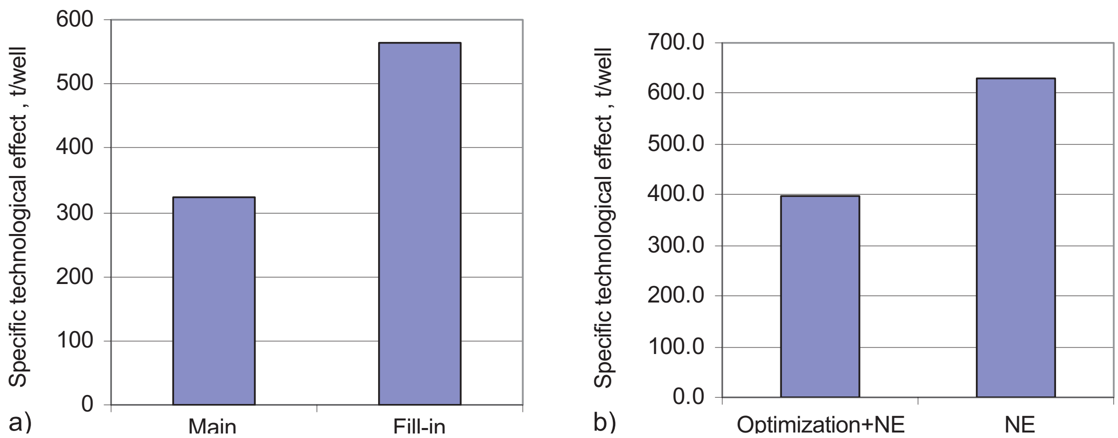

Fig. 5. Distribution of the effect of NE + MDFF on the wells of the main and fill-in stocks (a), along the wells with the use of optimization and without it (b)

of fluids. However, non-stationary water flooding increases the efficiency of the current development system even with a high difference in viscosity of oil and water.

The results presented in the paper showed that the expansion of non-stationary waterflooding to new sections of the field, characterized by different reservoir properties, demonstrated a significant effectiveness of NE. At the same time, it should be noted that the technology of NE on deposits of high-viscosity oil has the property of rapid aging, i.e. their technological efficiency is rapidly decreasing. Therefore, along with the expansion of the use of NE in new areas of the field, it is necessary to constantly modify the applied NE technology. This direction has good prospects for increasing the effectiveness of non-stationary exposure.

The development of NE technology at the Northern Buzachi field has passed a number of stages. Originally cyclic waterflooding was used, which showed a significant technological effect. At the next stage (at the present time), cyclic waterflooding was combined with the technology of changing the direction of the filtration streams. In the future, cyclic waterflooding in conjunction with the MDFF will be combined with the periodic operation of high-yield high-water-producing production wells.

The application of NE + MDFF in the NE section of the sixth block (south) showed the following features. Fill-in wells that have large mobile reserves in the drainage zone than the wells of the main stock are more responsive to the technology of changing the direction of the filtration flow and the cyclic action. The average specific effect of NE for fill-in wells is 1.7 times higher than for wells in the main stock.

The second feature is the fact that the subsoil user has massively used optimization of the operating modes of production wells (mainly the increase in liquid rates). The application of this type of geological and technical measures significantly affected the efficiency of non-stationary water flooding in the area under consideration. Wells with the use of optimization have an average of 1.5 times less specific effect.

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