Complex research of the application of the non-stationary waterflooding in interrelationship with other EOR methods

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Abstract: The article is concerned with the application of non-stationary waterflooding (NW) on the example of «LUKOIL-Western Siberia» fields. The experience of selection of candidate wells for NW has been analyzed, and the criteria for selecting an area for the application of the method have been developed, taking into account the conduct of other oil recovery enhancement operations (EOR) in the near regions. Recommendations are given on the use of NW in conjunction with other methods of EOR.

1. Introduction
Currently, many oil fields are characterized by high water cut, due to both the recovery of reserves, and premature water cutting of reservoirs with injected water.

In nonuniform stratums, injected water breaks into producing wells through highly permeable interlayers, leaving oil unallocated in low-permeability zones [1].

An objective necessity to cover the less permeable part of the productive formation by flooding with progressive watering of the formation is the restriction of water filtration in washed interlayers. Additional coverage of flooded areas and areas of the formation that are not involved can increase the oil recovery of reservoirs during normal waterflooding, prolongation of the water-free period, and decrease in the volume of water produced. One of the effective ways to achieve this goal can serve a NW (like cyclic waterflooding), which allows to affect the formation, both in the lateral and in the vertical section.

In contrast to the traditional waterflooding, the NW allows to cover the oil layers and stagnant areas of the formation that are not involved in the development, which contributes to an increase in oil recovery and a decrease in the relative volume of produced water [2].

2. Research
The purpose of this work was to study the application of NW in conjunction with other methods of EOR in the LUKOIL-Western Siberia fields.

In fact all of the company's fields are being developed with the use of maintaining reservoir pressure by waterflooding. The waterflooding system used does not always take into account the features of the geological structure and does not provide the necessary coverage by lateral and vertical section, as a result of which the development of many fields is characterized by insufficiently high oil recovery factors, low recovery rates of oil production and large volumes of produced water.

An important condition for the effective application of NW is the correct choice of the method for the production target, and determining the conditions for its application. Criteria for the applicability
of methods are determined on the basis of an analysis of the indicators of their implementation, the
generalization of the experience of introducing technologies in various geological and physical
conditions, the use of theoretical and laboratory research.

3. Results and discussion

3.1 Selection area for the waterflooding.
The choice of zones for NW is based on a multifactor analysis and is carried out using the methods
developed in KogalymNIPIneft, which allows identifying areas that are likely to be suitable for the
successful application of NW [3]. The analysis of information in the selection of zones includes the
rationale for the duration of the half-cycle of waterflooding for the geologic and physical reservoir
characteristics, the characteristics of the well stock, maps of the current state of development,
accumulated samples map, isobars, permeabilities and immovable oil, and log data. The algorithm for
selecting areas for NW is shown in Figure 1.

![Algorithm for selecting areas of NW and program development](image)

**Figure 1.** Algorithm for selecting areas of NW and program development.

At the first stage, the values of the complex parameter of the geological favorability (Fco) were
calculated from all the injection and production wells of the selected zone, based on the available data.
A map of the distribution of this parameter over the area of the object was constructed.
A geological model of the reservoir was developed for the selected areas, which takes into account
the connected heterogeneous part of the formation, i.e. the part in which vertical overflows are
possible due to uneven pressure redistribution.
For each layer, the following parameters are determined from the model: permeability \( k \), effective thickness \( h \), porosity \( m \) and oil saturation \( S \) (Table 1).

**Table 1. Results of calculating half-cycle of waterflooding at the areas of the Klyuchevoe Field.**

| Category interlayer                  | Layer characteristic | half-cycle, days |
|--------------------------------------|----------------------|------------------|
| Low-permeable coherent               | 28.3 0.45 0.21 0.65  |                  |
| Low-permeable insulated              | 33.6 6.69 0.21 0.59  | 30.8             |
| High-permeability insulated          | 219.6 3.59 0.23 0.64 |                  |
| High-permeable connected             | 176.2 0.93 0.23 0.65 |                  |

Next, the optimal operating frequency of the cycle change is determined by the formula:

\[
W_p = 2\chi / 12 \quad \text{or} \quad t = 12 / 2\chi. \tag{1}
\]

Here, \( W_p \) is the operating frequency of the flow oscillations; \( t \) – duration of the half-cycle of waterflooding; \( \chi = k/(\mu^a\beta_{pr}) \) – the average piezo-conductivity of a low permeable coherent interlayer; \( \beta_{pr} \) – reduced coefficient of compressibility of rock and fluid; \( \mu, m, l, k \) are the characteristic average viscosity, porosity, length and permeability of the formation, respectively [4].

Further, the current state of wells performance was analyzed, and the technical capabilities of the injection wells of the NW areas were considered.

The diagrams of injection wells stopping are selected according to the technology of NW implementation and the current state of the reservoir pressure maintenance system. At the company's fields in 2014 – 2015 during NW injection wells were stopped on a "one-by-one" basis or groups of wells operating in antiphase.

3.2 Approbation of the methodology

Approbation of this method of selection of areas for NW was carried out in 2013 - 2015.

The results of calculating the duration of the half-cycle of waterflooding and the effect of using NW on the company's fields using the methodology developed in the Branch are shown in Table 2.

**Table 2. Results of calculating the half-cycle time and efficiency of NW in 2014.**

| Field                | Facilities | Number of zones | The accepted distance to the front of displacement, l, m | Average coefficient of piezo-conductivity of the reservoir, m²/sec. | Duration of half-cycle, days | Viscosity of oil, mPa•sec. | Incremental ultimate recovery, thousand tons |
|----------------------|------------|-----------------|----------------------------------------------------------|---------------------------------------------------------------------|-----------------------------|-----------------------------|---------------------------------------------|
| Klyuchevoe           | BV         | 2               | 430/400                                                  | 0.03                                                                | 30                          | 1.82                        | 3.13                         |
| Nong-Eganskoe        | BV         | 1               | 530                                                      | 0.05                                                                | 30.73                       | 1.82                        | 4.09                         |
| Pokachovskoe         | AV         | 1               | 330                                                      | 0.03                                                                | 23.49                       | 1.75                        | -0.33                        |
| Las-Yoganskoe        | AV         | 1               | 800                                                      | 0.11                                                                | 32.3                        | 2.27                        | 3.60                         |
| Lokosovskoe          | BV         | 1               | 100                                                      | 0.07                                                                | 80                          | 2.78                        | -2.14                        |
| Urievskoye           | AV         | 4               | 800                                                      | 0.8                                                                  | 45                          | 2.45                        | 22.13                        |
| Vatjeganskoe         | AV         | 3               | 550                                                      | 0.03                                                                | 45                          | 2.55                        | 1.76                         |
| Povkhovskoye         | UV         | 6               | 500                                                      | 0.05                                                                | 28                          | 0.71                        | -2.04                        |
| Yujno-Vyintyoskoe    | BV         | 1               | 500                                                      | 0.03                                                                | 9                           | 0.43                        | 1.95                         |
| Tevlinsko-Russkinsko  | BS         | 2               | 600/775                                                  | 0.05/0.07                                                           | 38/53                       | 1.43                        | 4.00                         |
| **Total for 2014**   |            | **22**          |                                                          |                                                                      |                             |                             | **36.14**                    |
Along with NW, the measures for the formation of barriers in the pore space with washed reservoirs of a productive reservoir for water displacing oil technology (physical and chemical treatment) are relevant.

Tevlinsko-Russkinskoye field, where during the NW period, stops of high-water-producing production wells were conducted can be attributed to the experience of complex application of the methods.

Disabling high-water production wells contributes to a more uniform flooding of the formation. As a result of the application of such a scheme, more efficient displacement of oil from zones of the formation not covered by the exploitation is achieved. During the stopping of the injection wells of the second half-cycle, during the implementation of the NW production wells No. 7062 and No. 7064 were stopped with the aim of redistributing the injected water to the producing wells of the central row. The location of wells is shown in Figure 2 from the top. The regime of daily performance of these wells showed high efficiency: reduced water cut and increase in well performance (oil production rate) in surrounding wells. Figure 2 on the graphs shows the dynamics of the daily performance of these wells.

Figure 2. Fragment of the map of the zone with NW. Tevlinsko-Russkinskoye field. Change in the daily production of wells due the stop of production wells No. 7062 and No. 7064.
3.3 Integrated impact on formation
Consider the experience of the complex impact of NW and measures aimed at stimulation of production (forced fluid withdrawal, hydraulic fracturing, perforation of additional intervals). The implementation of such measures is carried out by increasing the pressure gradient in the zone of the formation affected by the well. The technologies of such integrated impact in the filtration process include the pressure readjustment between producing and injection wells with a change of direction of filtration flows in the formation.

The zone of Nivagalskooye field was used for pilot-industrial application of the method. The zone met all the criteria for efficient NW implementation and was characterized by good hydrodynamic cohesion of the reservoirs, their layer-by-layer and zonal heterogeneity, while the water cut in the area did not exceed 60%. The implementation of the NW, by stopping injection wells, began in June 2014. The use of (forced fluid withdrawal at the zone was carried out 1-3 months before NW, as shown in Figure 3.

![Figure 3](image.png)

**Figure 3.** Scheme for the implementation of the forced fluid withdrawal and NW at the zone of the Nivagalskooye field.

Horizontal wells on the zone were put into operation in late 2012 and early 2013. Compensation for fluid withdrawals by injection at the time of wells forced was 54 %. During the implementation of the NW, water injection volumes were reduced, despite the fact that it was recommended to maintain the pumping volumes at a stationary level, but the fall is permissible and was 20%.

Due to the forced fluid withdrawal and the shutdown of injection wells, the direction of displacement of the fluids changed, which led to an increase in fluid withdrawals and an increase in water cut in horizontal wells.

In production wells, the combined use of forced fluid withdrawal and NW led to an increase in water cut in production and fluid production by increasing the inflow of water from the underlying aquifers. The dynamics of the change in the water cut and well flow rates are shown in Figure 4. In horizontal wells (HW), fluid flow rates decrease due to the limitation of the volumes of injected water into the formation at the site. Reducing the volume of injection leads to a drop in depression and, as a consequence, to a drop in fluid withdrawals. When carrying out NW measures on sections with horizontal wellbore, it is necessary to strictly adhere to the basic requirements for effective
implementation of the NW for compliance with the levels of water pumped into the reservoir. The impact of NW on the operation of horizontal wells has not been adequately studied and requires further studies to determine the conditions for its successful application in areas that have such wells.

**Figure 4.** Characteristics of changes in water cut and oil production rates in the area of the forced fluid withdrawal and NW of the Nivagalskoe field.

In the majority of vertical wells, during the implementation of NW measures, the water cut of the products is periodically reduced. This indicates that during the periodic change in the water flood direction, oil is displaced to the faces of the operating oil wells from the stagnant and weakly drained zones.

As a result of the application of the NW method in combination with the forced fluid withdrawal in the section with horizontal wells in 2014, low efficiency was noted, additional oil production was 104 tons, the increase in water withdrawals at the area reached 18.8 thousand m$^3$.

NW at the company’s fields has shown quite good efficiency. In 2014, the additional oil production amounted to 39.7 thousand tons. During the period of its carrying out, as a rule, there is a periodic reduction in water cut of production and reduction of water withdrawals.

**4. Conclusion**

Complex application of the methods turned out to be quite effective, since the processes of redistribution of pressure gradients and interstitial overflows during the NW implementation increase the efficiency of address treatments by flow deviation compositions. Therefore it is recommended to treat by physicochemical methods in injection wells 3-6 months before the start of the NW implementation.

Stops of highly watered production wells during the NW period also have high efficiency. When the production wells stop, the pressure gradient increases, and in the case of cyclic waterflooding, a
condition is created in them to force the withdrawal of fluid from the formation with a change in the direction of the filtration flows due to the lithological heterogeneity of the formation as a zonal (lateral between the wells) and layered (between interlayers).

Measures to intensify oil production on the production well stock require enhanced reservoir energy in the drainage zone of the well.

Therefore, it is not recommended to carry out measures aimed at forced fluids withdrawal 2 months before the start of the NW implementation and during the period of its holding.

The proposed series of NW in conjunction with other workovers program makes it possible to increase oil extraction in complicated conditions for the exploitation reservoirs with hard-to-recover reserves, in highly-watered and low-productive reservoirs, related both to watering reservoirs with high reservoir properties and to the recovery of oil in low-permeability zones of facilities.

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