Development of the non-stationary waterflooding technology

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Abstract. The article analyzes the non-stationary waterflooding technology. The basic physical principles of the technology are described. The reasons for its low popularity among subsoil users are revealed. The article aims to substantiate the relevance of non-stationary technologies, conduct experimental-industrial works to adapt and create new non-stationary technologies, and determine conditions for their effective application. In the 1990s, Western technologies were widely used in the oil industry. Non-stationary waterflooding was not included in the list of these technologies. Despite its relative simplicity, the practical implementation of the non-stationary waterflooding technology requires preparation works. Non-stationary waterflooding is one of the most knowledge-intensive methods of enhanced oil recovery. Non-stationary waterflooding tends to "age", i.e. its effectiveness decreases over time, which requires constant changes in the technology and its combination with other methods.

1. Introduction

When developing highly productive heterogeneous reservoirs, due to the advanced waterflooding of highly permeable zones (layers, interlayers), oil reserves are uneven. At the same time, depending on the ratio of low-permeability and high-permeability layers, the ratio of viscosities of oil and water and other factors, the water cut can reach limiting values with low production rates from the initial recoverable oil reserves. The situation when the water cut reaches and even exceeds limiting values, and significant volumes of mobile oil reserves remain in the reservoirs is common in the development of oil fields. This is especially evident in high-viscosity oil deposits.

This paper discusses the development of non-stationary waterflooding technology. Non-stationary waterflooding is a common sweep enhancement technology in the development of reservoirs with heterogeneous permeability. The implementation of non-stationary waterflooding does not require additional costs, and the effect of the technology is significant. Therefore, this technology is widely used in the development of oil fields. To date, extensive experience in the use of non-stationary waterflooding under various geological and technological conditions has been accumulated. Basically, non-stationary waterflooding has been applied for oil reservoirs with low and medium viscosity. For example, the Romashkinskoe field has been a testing ground for various types of non-stationary impacts. There are also reports on the use of the NT on oil deposits with an increased viscosity.

2. Materials and methods

The problem of developing oil reserves from a heterogeneous formation has been well studied in underground hydrodynamics. A sector model of a heterogeneous reservoir was built. The information
was processed using modern methods. An analysis of the non-stationary waterflooding technology showed that it has been implemented in practice and the results of implementation have confirmed its effectiveness.

3. Results
The model is described in [1]. The situation when viscosities of the displaced agents were comparable by \( \mu_o / \mu_w = 1.25 \) is analyzed.

Figure 1 shows the waterflooding of the model formation. As expected, there is a rapid breakthrough of water through the highly permeable interlayer. With full flooding of a highly permeable interlayer, the maximum water cut is achieved. At the same time, residual oil reserves are concentrated in low-permeability intervals of the formation.

![Figure 1. Changes in water saturation and pressure during flooding of a heterogeneous formation (according to [1])](image)

As a result of the advanced flooding of the highly permeable layer, a technogenic oil-water contact is formed. It has a significant strike area. By creating conditions for the exchange of fluids between the flooded and oil areas, it is possible to use residual reserves of the partially flooded formation. In this case, the high-permeability layer becomes a transport channel for the oil flowing from the low-permeability layers.

The ability to create pressure drops between the water-flooded and oil intervals is inherent in the non-stationary (waterflooding) technology. The literature also refers to it as the “elastic-capillary cyclic development method” [3,12].

The physical foundations of unsteady flooding were developed in the 1960s. In 1965, a number of scientists from the All-Russian Research Institute (Surguchev M.L., Zheltov Yu.P., Boxerman A.A., Gubanov A.I., Ogandzhanyants V.G., Kocheshkov A.A.) formulated the basic principle of the NS technology: “The method involves increasing the elastic reserve of the reservoir system by increasing and decreasing the water injection pressure. This is a prerequisite for the unsteady pressure drops within the formation and the corresponding unsteady fluid flows between layers (areas) of different permeability. In the half-cycle of increasing the injection pressure, water from the layers with higher permeability penetrates into the low-permeability layers, and during the half-cycle of pressure reduction, oil from the low-permeability layers moves to the highly permeable part of the reservoir.”

As a result of waterflooding of heterogeneous layers, undrained residual oil reserves are located in low-permeability layers, zones, areas. Initially, a fairly homogeneous field of the oil-saturated reservoir is cut by flooding zones; "under such conditions, the formation is a random alternation of flooded and oil-saturated areas" [5]. The transition to the non-stationary water injection will allow the remaining oil reserves to be involved in the drainage process.

Studies of the physical processes occurring during periodic water injection are summarized by V.E. Gavura. According to the researcher, “the effectiveness of the elastic-capillary cyclic method of waterflooding of heterogeneous formations is determined by two inextricably linked processes: the introduction of water into low-permeability zones of the formation due to pressure drops arising from an uneven distribution of pressures caused by the heterogeneity of the formation, and capillary
retention in low-permeability zones of the formation of penetrated water” [2].

The NST is often combined with the flow reversal (FR) technologies. In this case, the combination of technologies makes it possible to obtain an effect determined by the non-stationary processes in the formation and changes in the direction of the predominant flows of formation fluids. The integrated technology increases the coverage of the reservoir by acting along the section and the lateral [4,9].

In practice, an unsteady pressure field is created by regular shutdowns (or changes in injectivity) of injection wells and / or high-water-cut production wells. Methods for creating regular fluctuations of the pressure field can be combined. The main advantage of non-stationary waterflooding is its low cost; no capital costs are required to implement the technology, and there is no increase in operating costs. The non-stationary waterflooding allows us to obtain a significant effect. According to the expert assessment, the effect value varies from 8% to 14% of the cumulative oil production. For high-viscosity oil deposits, an increase in oil production is 12 ... 20% [11], for low-viscosity oil deposits, it is 6 ... 14% [6].

The effect value is determined by many parameters: the permeable heterogeneity of the reservoir, the initial water cut, the ratio of viscosities of oil and water, the impact amplitude (from the side of injection wells), the duration of shutdowns and operation of injection and production wells, the type of a waterflooding system, etc.

According to Vladimirov, “the use of non-stationary waterflooding technologies has provided a significant effect. However, non-stationary waterflooding technologies have a decreasing efficiency during their long-term use. It is necessary to adapt the NS technology to the changing geological and technological conditions. Therefore, the applied technologies undergo continuous changes.

According to [8], non-stationary stimulation technologies multiply their efficiency when rebuilding the reservoir pressure maintenance system (for example, when transferring water injection foci). However, this way of increasing the efficiency of the NS technology is costly and requires a significant amount of time to be implemented. However, [7] has shown that other ways of increasing the efficiency of non-stationary technologies can be used. They involve the use of other modes of regular operation of injection wells.

The commonly used method for reducing the water cut are technologies limiting the water inflow and flow diverting technologies [10]. These types of technologies limit the movement of water through highly permeable intervals of the reservoir due to the injection of special plugging compounds. A sustainable positive effect can be achieved by pumping large volumes of plugging compounds. Otherwise, the impact area is limited to the near-wellbore zone, which is often insufficient to obtain a positive economic effect.

Unlike costly technologies for limiting water production and flow diversion technologies, non-stationary waterflooding (NSWF) is a free technology. The use of non-stationary waterflooding technologies at the fields of the former Soviet Union is technologically and economically efficient. At the same time, it should be noted that the theory and practice of non-stationary waterflooding were developed for conditions when the water cut is significantly lower than the limit values. However, currently, the conditions for the development of these fields have changed, which requires further studies of non-stationary processes and adaptation of the NSWF technology to the current conditions.

4. Conclusion
The data obtained demonstrates the attractiveness of non-stationary waterflooding technologies in the development of oil deposits, especially those that are at the final stage of development. However, the NSWF technology is not widely used. After its rapid development in the 1970-1980s, the oil recovery technology was beyond the scope of the most popular enhanced oil recovery (EOR) technologies. This is due to a number of circumstances. Firstly, in the 1990s, specialists used Western technologies. Despite the successful use of the non-stationary waterflooding, it was an “exotic” method of enhanced oil recovery for Western specialists. There was a gap between the rich experience of the Soviet school of petroleum science and the current understanding of oil field development. Secondly, despite its relative simplicity, the practical implementation of the technology requires preparation works. Non-stationary waterflooding is one of the most knowledge-intensive methods of enhanced oil recovery. Therefore, the NSWF programs are being developed by specialized scientific and design
organizations. It is possible to distinguish between three directions in preparing this technology for implementation: selection of a site, selection of a NS technology and its parameters, coordination of the technology with capabilities of reservoir pressure maintenance and collection systems. Thirdly, the NS technology tends to “age”, i.e. its effectiveness decreases over time. The oil recovery technology is quickly aging at high-viscosity oil deposits. This requires constant changes in the technology, its combination with other methods.

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