Changes in formation pressure and technological efficiency of unsteady flooding in double permeability reservoirs having different productivity rates

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Abstract. Unsteady waterflooding went through several stages. Within the pilot works in April 2009, cyclical water injection was started in Block 7 (central section). In addition, alternate water injection into the horizons of the Jurassic and Cretaceous sediments of Block 10 began. For this purpose, injection wells equipped with devices for simultaneous separate water pumping were used. The significant effect of non-stationary waterflooding in the experimental sections allowed for the application of the technology in other blocks. The technology implementation scheme was applied for injection wells of Blocks 6 and 10. Since July 2010, cyclic injection has been used for many wells. Periods of non-stationary operation of injection wells were determined experimentally. The reservoirs with heterogenous permeability containing highly permeable and low-permeable layers are the most optimal ones. The heterogenous structure of the reservoir provides a large contact area between layers with different permeability levels which allows for non-stationary effects due to the occurrence of overflows between the layers. It can reduce the water content of the products and increase oil production.

1. Introduction
The higher the permeability of the reservoir fracture system, the higher the effect of cyclic water injection is. The article analyzes the results of numerical experiments using a double permeability reservoir model with different productivity rates.

The main problem is conditions for comparing development options. The hydrodynamic problems are multicriteria, i.e. their decisions are determined by many factors. The parameters describing geological and physical properties of the formation, its reservoir and saturating fluids are unchanged, while technological factors can change depending on the development option. It is difficult to compare technological development indicators in order to obtain information about the efficiency of the technology used. For example, by comparing the base option and the one with cyclic water injection, you can see that they differ both in output (oil production, liquids, water content, formation pressure) and input indicators (starting values of fluid flow rates, injectivity, operating modes of injection wells, etc.). Since the unsteady flooding implies a periodic shutdown of injection wells, the dynamics of
formation pressure differs from the indicators of the base option. In this case, it is difficult to separate UF effects and formation pressure modification effects for the whole deposit. Therefore, the main criterion for comparing the two options is coincidence of the dynamics of accumulated volumes of water injected into the formation [1, 2, 10].

2. Materials and methods
The tasks were solved by analyzing and synthesizing high-viscosity oil deposit development and operation modes. The analysis of efficiency of the unsteady waterflooding technology in high-viscosity oil deposits was carried out by processing statistical information. Theoretical studies of non-stationary processes were carried out using hydrodynamic simulators used in the oil industry.

3. Results
Stationary and non-stationary modes of operation of injection wells for reservoirs with fracture permeability varying from 1 to 50 μm² were analyzed. Permeability of pore blocks remained unchanged (0.05 μm²). The unsteady flooding began when the water production rate reached 90%. The duration of half cycles for all tasks was 30 days.

The main condition for comparing the options is coincidence of the dynamics of accumulated volumes of injected water which was carried out by selecting an appropriate coefficient of compensation for fluid withdrawals by water injection [3].

For the options with “low” permeability of the fracture system (permeability rates were 2 μm² and 5 μm²), it was impossible to achieve complete coincidence of the dynamics of accumulated volumes of water injected into the formation. This is due to the fact that selection of the compensation coefficient is limited to low values of fluid flow rates and well injectivity. If the compensation coefficient is less than 2, the formation pressure sharply decreases. If the coefficient is more than 2, the pressure sharply increases. For large permeability rates (more than 10 μm²), it was possible to achieve complete coincidence of the dynamics of accumulated volumes of water injection.

Depending on the permeability of the fractured reservoir system, changes in the technology are significantly different. For “low-permeable” fractures (Kᵢ = 2 μm²), the use of the technology decreases oil production. The water content decreases, i.e. the quality of oil displacement increases (a larger amount of oil for equal volumes of produced fluid). In this case, unsteady waterflooding causes a decrease in the water content, but oil withdrawal rates are below base levels due to the decreasing formation pressure. With an increase in the formation pressure, the oil production rate increases and becomes higher than the base value, but the water content increases up to the base level. In this case, non-stationary waterflooding as a method used for oil recovery enhancement cannot be used. Indeed, as noted in [5–7], a significant increase in the pressure (the fracture system is water-flooded) prevents the oil from flowing into the non-flooded pore blocks.

At higher permeability values of the reservoir fracture system, a short-term decrease in the average formation pressure can be observed after implementation of the technology. Then the formation pressure is rising [4, 8].

The reaction of the system to the cyclic water injection for the fracture permeability value equal to 5 μm² is indicative. It can be seen that during the initial period of application of the UF technology, a short-term decrease in formation pressure occurs. This reduces the water content due to the fact that a decrease in pressure in the fracture system contributes to the oil flow from the pore blocks into the cracks under cyclic exposure. A further sharp increase in formation pressure increases oil production and watering.

This period can be considered as a period of cyclic impact mode formation (transition period) which determines the cyclic nature of changes in the oil production rate relative to a certain average value.

The higher the permeability of the fissure system, the shorter the duration of the transitional period of cyclic exposure. This is due to the absence of a period of negative efficiency for a reservoir with highly permeable fractures, since the transition period lies within the time step of the output.
The use of non-stationary effects increases formation pressure relative to the base stationary injection. This is evident for the options with permeability which is above 10 μm² and it is possible to achieve a complete coincidence of the dynamics of accumulated water injection volumes for stationary and non-stationary operating modes of injection wells. However, the higher the permeability of the reservoir fracture system, the smaller the increase in formation pressure is. At maximum permeability of fractures of 50 μm², the formation pressure during unsteady waterflooding is lower than the formation pressure for the base option. However, this does not affect the efficiency of the unsteady waterflooding technology.

If we consider the entire period of the deposit development (when the maximum water content (985) can be achieved), unsteady waterflooding can significantly reduce the water content in the extracted products and increase the profitable period of reservoir development (Table 1) [9].

### Table 1. Technological indicators of development options for high-viscosity oil formations with a double permeability reservoir with different fracture permeability values.

| Collector permeability, mD | Base option | Oil reserves | Increase |
|---------------------------|-------------|-------------|----------|
|                           | Permeability of pore blocks – 50 mD |             |          |
| 2000                      | 0.158       | 0.163       | 0.005    |
| 5000                      | 0.168       | 0.190       | 0.023    |
| 10000                     | 0.158       | 0.195       | 0.037    |
| 20000                     | 0.141       | 0.192       | 0.050    |
| 30000                     | 0.131       | 0.189       | 0.058    |
| 40000                     | 0.123       | 0.186       | 0.063    |
| 50000                     | 0.116       | 0.180       | 0.064    |

The increase in the final oil production rate under unsteady waterflooding is due to a longer development period and a higher oil extraction rate.

### 4. Conclusions

The presented research results on the use of non-stationary waterflooding at deposits of high-viscosity oil with double permeability reservoirs allow for the following conclusions:
- the reaction of the development system under the transition to a non-stationary mode of operation of injection wells takes a certain time interval - a transition period. During this period, the efficiency of unsteady flooding can be negative. The higher the permeability of fractures, the shorter the transition period is;
- for a reservoir with “low-permeable” fractures (low productivity), the use of unsteady flooding decreases the rate of oil production. This reduces the water content in the extracted products;
- for a reservoir with highly permeable fractures (high productivity), the use of non-stationary waterflooding increases the rate of oil recovery and reduces the water content in the extracted products.
- for the maximum permeability of the fracture system, a relative increase in accumulated oil withdrawals for the base development period was 21 % which indicates the high efficiency of the UF technology for development of high-viscosity oil deposits with double permeability reservoirs.

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