Application of the non-stationary waterflooding technology and periodical operation of production wells for heterogeneously permeable reservoirs

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Abstract. Application of the non-stationary waterflooding technology at the Kumkol field (the Republic of Kazakhstan) had a number of unsolved problems. The main problem is correct selection of parameters for the non-vascular flooding technology - an amplitude and a cycling impact frequency. The amplitude of impact is determined by the capabilities of the reservoir pressure maintenance system (RPM) and the ability of the reservoir to absorb large volumes of water. The impact frequency is a more unstable parameter depending on the structure of the reservoir and saturation of heterogeneous fluids. For the Kumkol field conditions, the void reservoir space has a complex multi-level structure. There are pore reservoirs with different permeability rates, highly permeable layers located over the deposits, filtration channels with very high permeability (cracks, a super collector). In addition, there are three phases of reservoir fluids (oil, water, free gas). All this creates uncertainty in setting frequency parameters of the non-stationary waterflooding method. The article deals with the issue of determining frequencies of impact.

1. Introduction

When developing highly productive reservoirs with heterogeneous permeability, uneven production of oil reserves is due to the advance flooding of highly permeable zones (layers, interlayers). Depending on the ratio of permeability of low-permeable and high-permeable layers, the ratios of viscosities of oil and water, and other factors, the water cut of extracted products can reach limit values at low production rates. When the water cut reaches or even exceeds limit values, and significant volumes of mobile oil reserves remain in the reservoirs is typical when developing oil fields [1–4].

As a result of the advance flooding of the highly permeable layer, a technogenic oil-water contract zone is formed. When creating conditions for the exchange of fluids between the flooding and oil areas, it is possible to use residual reserves of a partially flooded formation. In this case, the highly permeable layer becomes a transport channel for oil flowing from the low permeable layers.

The technology of non-stationary impact (waterflooding) has the ability to create pressure differences between the flooded and oil intervals of the reservoir. It is referred to as an “elastic-capillary cyclic development method” [5–7].
The mathematical model of three-phase filtration was used to study the development of oil reserves using the CWI + PWP method. As a research tool, the 6.7.1 hydrodynamic modeling package Tempest-More (Roxar) was used [9].

Let us analyze the reservoir area of 1000×1000×10 m. Initial oil saturation of the reservoir varies from \( S_0 = 0.86 \) in the sole to \( S_0 = 0.87 \) in the roof. Initial reservoir pressure and temperature are \( P_0 = 11.6 \) MPa, \( T_0 = 51 \) °C. Water density and viscosity are 1.10 g/cm\(^3\) and 0.83 cP, respectively. Oil density is 0.800 g / cm\(^3\). Oil viscosity is 2.7 cPz, gas content is 19 m\(^3\)/m\(^3\). Oil saturation pressure with gas is 4.5 MPa. These conditions correspond to the real object – M1 horizon of the Kumkol field (the Republic of Kazakhstan).

The injection and production well were located in rows. The average distance between injection and production wells varies from 320 to 450 m.

Technological conditions for the development of a deposit site are as follows. All production and injection wells are launched simultaneously. The entire layer depth is perforated. For injection wells, the maximum injectivity threshold is 1000 m\(^3\)/day at maximum bottomhole pressure of 20 MPa. There are no restrictions on production wells operation.

For all the options, calculations are carried out until the maximum water cut of extracted products reaches 98%.

An additional condition for comparability of the results is coincidence of the dynamics of the accumulated volumes of injected water for the base and corresponding options with unstationary waterflooding. This requirement made it possible to exclude the influence of a significant increase (decrease) in reservoir pressure during non-stationary waterflooding on effects comparison results. All the above conditions are unchanged for all the hydrodynamic problems.

Let us study effectiveness of non-stationary effects on the example of a reservoir with a layer of inhomogeneous permeability at different values of the permeability coefficient of low-permeable layers. Permeability of the highly permeable layer was fixed and the values of low permeable layers were changed. To compare the results obtained for different values of reservoir permeability, let us assume that reservoir porosity (and geological oil reserves) is the same for all the options. The reservoir porosity is \( m = 0.29 \) u.f. Initial geological reserves of oil are 2611.6 thousand m\(^3\).

A reservoir consisting of three hydrodynamically related layers which has heterogenous permeability was used as a model of the heterogenous reservoir. In the middle of the formation there is a highly permeable layer with a fixed value of permeability coefficient \( K_{hi} = 2.0 \) \( \mu \)m\(^2\). Low-permeable layers are located above and below the section. Their permeability varies from 0.001 to 0.1 \( \mu \)m\(^2\) depending on the option. All layers have equal thicknesses.

**2. Methods and materials**

The results obtained are based on the use of hydrodynamic simulators tested and recommended for use in the oil industry. For processing of field data, PC-based analysis methods were used. The recommendations were field tested with a positive technological effect.

The results were used for planning and implementation of the non-stationary waterflooding program and periodical operation of production wells in the Kumkol field.

**3. Results and discussion**

Let us assume that when the water cut of 95% is reached, the reservoir development system goes into a non-stationary operation mode. The injection wells are switched off for 10 days while the production wells operate, then the injection wells begin to pump water and the production wells are switched off for the next 10 days. Then the cycle repeats. When the water cut of 95% is reached, all the wells stop operating.

A series of numerical experiments was carried out. The following reservoir properties were set: permeability of the high-permeable layer remained unchanged and was equal to 2.0 \( \mu \)m\(^2\), permeability of the low-permeable layers was 0.10; 0.05; 0.01 and 0.001 \( \mu \)m\(^2\). “Initial” water cut was 95%. For each
task, two options were considered: basic (stationary well operation) and non-stationer well operation (cyclical water injection and periodic out-of-phase fluid uptakes (CWI + PWP)).

Figure 1 shows the dynamics of technological indicators (oil production rate and water cut) for the basic option and the CWI + PWP option when permeability of low-permeable layers is 0.01 µm². It is clearly seen that the use of the CWI + PWP technology can significantly improve current development indicators - the oil production rate increases and the water cut of extracted products decreases. However, production wells are idle for a certain period which can decrease the production rate.

**Figure 1.** Dynamics of the current indicators of oil production rate (a) and water cut (b) for the base and CWI + PWP methods. Permeability of low-permeable layers is 0.01 µm²

Figure 2 shows the changes in current technological development indicators related to the application of CWI + PWP technology. For the convenient viewing, the points corresponding to the well operation stoppage were removed. The relative change in the oil flow rate of the area, i.e. the amount of deviation from the base option in the shares of the base option

\[ \eta = \frac{\alpha_{\text{CWI}} - \alpha_{\text{base}}}{\alpha_{\text{base}}} \]

was analyzed.

**Figure 2.** Relative changes in oil production rate (a) and absolute change in water cut (b) by applying the CWI + PWP technology for the reservoir with a heterogeneous permeability layer with different permeability values of low-permeable layers.
Thus, the use of the CWI + PWP technology can significantly improve the efficiency of oil recovery. In comparison with the non-stationary water-flow considered in [6–8, 11], the effect of joint non-stationary effects in the injection and production areas is more significant. The oil production rate increases by 8 times, and the water cut decreases by 14%.

Application of the CWI + PWP technology allows for extraction of additional oil and reduction of associated water production which is important for modern development of the Kumkol field.

Let us present conclusions on the use of non-stationary flooding for the field with a heterogeneously permeable reservoir. The table presents the final results of model calculations.

Table 1. The results of model calculations of technological indicators for the options with heterogenous permeability of the reservoir (the CWI + PWP method).

| Permeability of the low permeable layer, md | The ratio of permeability of high-permeable and low- | ORC, u.f. | Increase in the ORC, u.f. |
|-------------------------------------------|---------------------------------------------------|----------|--------------------------|
|                                           | permeability of the low permeable layer, md       |          |                          |
| 100                                       | 20                                                | 0.623    | 0.668                    | 0.045 |
| 50                                        | 40                                                | 0.601    | 0.654                    | 0.053 |
| 10                                        | 200                                               | 0.535    | 0.614                    | 0.079 |
| 1                                         | 2000                                              | 0.346    | 0.589                    | 0.242 |

Thus, the CWI + PWP technology helps increase an oil recovery rate. It should be noted that water production decreases. Even at highly permeable reservoirs with homogenous permeability, liquid production decreases by 5% at a lower technological oil production effect (1.3%). The dependences of the final ORC on permeability of low-permeable layers are shown in Figure 3.

Figure 3. Dependances of the ORC and ORC increments due to CWI + PWP on the permeability of low-permeable layers of a heterogeneous reservoir.
4. Conclusion

The results of hydrodynamic calculations showed that non-stationary waterflooding combined with periodical operation of production wells has positive efficiency in reservoirs with a large range of heterogenous permeability values. In flooding, both in the injection and in the selection area, for various reasons (permeability heterogeneity, gravitational phase separation) a contact surface is formed between the water-flooded and oil-saturated reservoir areas which have different piezoelectricity. Non-stationary impact (CWI + PWP) intensifies the exchange of fluids between these areas which ensures a positive technological effect. This effect is different for inhomogeneous and highly inhomogeneous reservoir permeability, i.e. it depends on the value of permeability heterogeneity.

Thus, the use of cyclic water injection with periodical operation of production wells in the antiphase allows for extraction of additional oil and reduction of associated water production which is important for modern development of the Kumkol field.

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