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Improving the Efficiency of Pulsed Non-Stationary Flooding of Hydrocarbon

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***Abstract* — The method of pulsed non-stationary flooding is a continuous regulatory process. Its optimal variant is determined by the stage of development of reserves. It is selected after a thorough analysis of the development, when the current oil reserves are determined differentially by zones and sections of the reservoir and the forecast of the dynamics of their extraction under the existing development system is given. Then the comparison of the development indicators of pulsed non-stationary flooding options with the ones for the existing (non-stationary) acting system is conducted, and the optimal variant is chosen.**

***Keywords* — elastic-capillary; effect; block; dispersed pattern-type; heterogeneities; acceleration; injection; fluid.**

I. Introduction

The effectiveness of pulsed non-stationary waterflooding as a method of regulating development largely depends on the successful selection of the most rational option, taking into account the specific conditions of field development. The accumulated preliminary experience in the implementation of pulsed non-stationary waterflooding (with additional installation of the impulse device at the downhole or at the wellheadof the injection well) indicates the need for a cautious approach to determining the extent of its implementation, especially in the newly commissioned fields. Variants of the method, which envisage a reduction in the volumes of water injection, are only acceptable for flooded deposits with mechanized recovery of liquid.

The method of pulsed non-stationary flooding is a continuous regulatory process. Its optimal variant is determined by the stage of development of reserves. It is selected after a thorough analysis of the development, when the current oil reserves are determined differentially by zones and sections of the reservoir and the forecast of the dynamics of their extraction under the existing development system is given. Then the comparison of the development indicators of pulsed non-stationary waterflooding options with the ones for the existing (non-stationary) acting system is conducted, and the optimal variant is chosen [1-3].

To assess the results of pulsed non-stationary flooding and to develop the measures to improve its efficiency, it is important to find out the ratio of effects from capillary imbibition of closed pores during pulsed injection and the change in filtration direction during pulsed non-stationary flooding. In this case, downhole or wellhead devices (generators, vibrators, pulsers, etc.) are used for operating injection wells to conduct water injection in order to simultaneously accelerate the reverse capillary impregnation of closed oil-bearing zones and change the direction of filtration of the injected water [4-6]. Pilot tests of this complex flooding were carried out at the fields of JSC Samaraneftegaz in 2015-2016.

II. Materials And Methods

It is known that the condition for the efficiency of elastic-capillary flooding is compliance with the duration of a half-cycle within the limits of $t = \frac{R_K^2}{4x \cdot 0.5}$ where R_{eb} is the radius of the external boundary, x is the piezo-conductivity of the reservoir. If to accept R_{eb}=500 m, $x - = 10^4\ cm^2/_s$ (average parameters), then the specified condition is realized at t>48 h, i.e. it was carried at all fields. However, for a number of fields (Neprikovskoe, Mitiaevskoe and Lebedinskoe) there is no positive effect. Let us find out the conditions for obtaining the effect of changing the direction of filtration when changing the mode of operation of injection wells.

Obviously, such an option is optimal, in which the effect of capillary imbibition is complemented by the changing of filtration direction, which favors the advancement of the injected water.

In pattern-type development systems, these conditions are fulfilled due to the geometry of the net of injection and production wells.

In block systems, the features of the mutual positioning of injection and production wells allow a variety of change of their operation modes (single, group, blocks, etc.). Therefore, it is necessary to take into account the impact of the sequence of changes in the operating modes of the wells on the final effect of pulsed non-stationary flooding to choose the most rational option according to specific conditions.

A strict analytical decision to determine the quantitative effect and pulse non-stationary flooding in the formulated statement poses significant difficulties. However, when solving a number of practical problems, in particular, choosing its expedient option, it is sufficient to obtain a comparative characteristic of the process efficiency. In block development systems, the criterion for the comparative efficiency of pulse non-stationary flooding can be the magnitude of the change in the filtration rate along a line parallel to the pumping row. The choice of this parameter as a criterion is due to the following provisions.

It is known that the advance breakthrough of the injected water to the bottom of producing wells occurs along a narrow strip in the direction from injection wells to producing wells, since it is here that the pressure gradients are maximal. Therefore, to solve the problems of uniform oil displacement and of an increase in the period of water-free production it is enough to increase the flow of injected water in a direction parallel to the pumping row. An indicator of the intensity of injected water in this direction is the corresponding component of the filtration rate. The magnitude of the change in the filtration rate component in any direction does not give absolute values of oil recovery, reduction of flooding parameter, etc. It allows one to get a comparative assessment of various options for changing the mode of operation of the injection wells, in which the effect of capillary imbibition is complemented by the effect of changing the direction of filtration of the liquid.

Let us now consider the effect of the elastic-capillary cyclic method of displacing oil with water on the acceleration of capillar imbibition of blocks. To practically implement this method it is necessary to periodically change the pressure or fluid flow at the boundaries of the reservoir. It will result in a periodic change in the parameters of capillary imbibition at the contact of high permeability and low permeability reservoir objects.

During the period of the pressure increase cycle, the oil in the porous blocks, lenses or interlayers is compressed and water enters into them. When the pressure is reduced, the reservoir contents (oil and water) expand, but water is retained by capillary forces in those heterogeneities into which it has penetrated, and oil comes out of them.

In the mechanism of elastic-capillary cyclic effects, there are two effects on which the efficiency of this method depends. One of these effects is the acceleration of water penetration into the heterogeneities, which is achieved due to an increase in the average pressure drop between them. The second effect is capillary retention of water in heterogeneities.

To assess the effect of accelerating the penetration of water in heterogeneities, we examine a fractured-porous reservoir using the equation of fluid exchange between blocks and fractures [7]

$$\frac{d\upsilon}{dt}+\frac{\alpha}{\mu}\left(\frac{\upsilon}{\beta_2}+\frac{dp}{dt}\right)=0. \tag{1}$$

We set $p = P\sin\omega t$, $\omega = 2\pi/\Theta_0$ (Θ_0 – is the period of the pressure change cycle). Then from (1) we have

$$\frac{d\upsilon}{dt}+\frac{\alpha}{\mu}\left(\frac{\upsilon}{\beta_2}+P\omega\cos\omega t\right)=0. \tag{2}$$

The solution to equation (2) is expressed as follows:

$$\upsilon=\exp\left(-\frac{\alpha}{\mu\beta_2}t\right)\left[\int\frac{\alpha P\omega}{\mu}\cos\omega t\exp\left(\frac{\alpha t}{\mu\beta_2}\right)dt+C\right]. \tag{3}$$

As a result of mathematical transformations, we obtain an expression for determining the rate of fluid penetration in heterogeneity.

$$\upsilon=\frac{1}{e^{bt}}\left\{\frac{2\alpha}{\mu}\left[\frac{a^2e^{bt}}{b^2}(bt-1)-\frac{\sqrt{P_{\min}}\,a\cdot e^{bt}}{b}\right]+C\right\} \tag{4}$$

Given the stationarity of the appearance of pulses in a fluid, i.e. $\upsilon(a,t)=\upsilon(t)$ the particular solution to equation (4) will be

$$\upsilon=\frac{2\,\alpha\,a}{\mu\,b}\left[\frac{a}{b}(b\,t-1)-\sqrt{P_{\min}}\right] \tag{5}$$

$$a=\frac{\sqrt{P_{\max}}-\sqrt{P_{\min}}}{\varphi_1}\,\omega;\; b=\frac{\alpha}{\mu\beta_2} \tag{6}$$

α – coefficient characterizing the intensity of fluid exchange between the system of blocks and the system of fractures; μ – oil viscosity, Pa/s; ω – angular frequency, rad/s, β_2 – elasticity of blocks, 1/Pa; P_{max}, P_{min} – maximum and minimum values of the amplitude of the pressure in the impulse of a liquid, Pa.

The average for the cycle the flow of fluid in one direction (for example, from fractures into blocks), taking into account the introduced notation (6), finally, after transformations, will look like:

$$\overline{\upsilon}=\frac{2\alpha\,at_1}{T\mu b}\left[\frac{a}{b}\left(\frac{bt_1}{2}-1\right)-\sqrt{P_{\min}}\right] \tag{7}$$

where T – is the period of the pressure change cycle , c; t_1 – - the period corresponding to the moment of increase in pressure, s.

According to the obtained formula (5), the dependence υ = f (t1) is plotted at various pulse frequencies of the liquid (Figure 1), as well as the dependence according to formula (7) = f (ΔP, at Pmax = const), which is shown in Figure 2, with the following initial data: we choose the parallelepiped (e x e x d = = 20 x 20 x 200 cm) as the test rock, then [8]

$$S_y^2=\left[\frac{2(e+2d)}{ed}\right]^2=\frac{4(e+2d)^2}{e^2d^2}=\frac{4(20+200)^2}{20^2\cdot100^2}=0{,}048\ \text{1/cm}^2; \tag{8}$$

Where $\alpha = k_2 \cdot S_y^2 = 10^{-10}\cdot 0.048 = 48\cdot10^{-7}$; μ = 10 cP (centiPoise) ; $\beta_2 = 10^{-9}$ 1/Pa; $P_{мах}$ = 10 MPa; $P_{мin}$ = 1 MPa.

As $\overline{\upsilon}$ is the volume of fluid flowing from the blocks into the fractures per unit time per unit volume of the fractured-porous formation, the total volume of the fluid per unit volume of the fractured-porous medium will be m = m1 + m2 = 0.14 + 0.20 = 0.34.

Then, provided that water flows into the block, and oil flows out of it, it is possible to determine the time for displacing oil with water in the selected sample.

$$t=\frac{m}{\upsilon}. \tag{9}$$

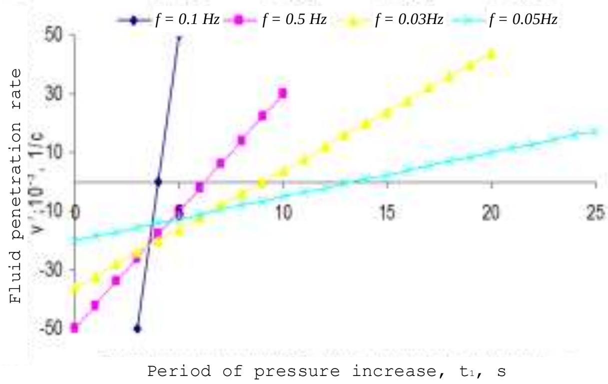

Fig. 1. Dependence of the fluid penetration in heterogeneities on the period corresponding to the moment of pressure increase.

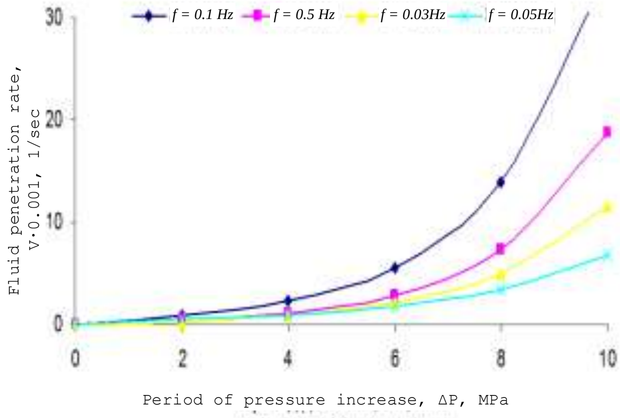

Fig. 2. Dependence of the average rate of fluid penetration in an heterogeneity on the pressure drop.

As can be seen from the graphs shown in Figure 1 and Figure 2, with an increase in the frequency of oscillations at a given parabolic law of pressure change, the rate of penetration of fluid into a fractured-porous formation increases dramatically. As for the change in pressure drop, then it should be noted that the effective penetration of the liquid starts from the value of the pressure drop of 6-7 MPa, with an increase in the oscillation frequency – this value can be reduced.

However, as mentioned above, it is not enough just to "inject" water in heterogeneity - it is important that in part of the cycle, when the pressure decreases, capillary forces keep water in heterogeneities and oil comes out of the rocks. To obtain qualitative estimates, let us consider the following idealized process. Let the parallelepiped sample of a porous medium be initially filled with a less wettable phase. The side surfaces and one of the end faces are assumed to be impermeable, while the free end is brought into contact with the wetting fluid at the initial moment. As a result, the process of countercurrent capillar imbibition will begin, i.e. the wetting phase will be absorbed, and the non-wetting phase will exit through a single open end surface. Obviously, the absorption will occur mainly in small pores, and the output of non-wetting phase - in large ones.

As shown by countercurrent impregnation experiments carried out on transparent samples [9, 10], filtration of both phases in opposite directions occurs uniformly throughout the flow, and each phase moves along its own pore channel system. Countercurrent imbibition can therefore be considered in terms of concepts adopted for ordinary one-dimensional two-phase filtration. The relative permeability for countercurrent flow may differ from the corresponding functions in the case of unidirectional flow of both phases. However, in further qualitative study this distinction is not taken into account.

III. Results And Discussions

As a result of experimental studies [10] of water retention in heterogeneities under cyclic exposure, it was shown that the time required for the water injected in the heterogeneity to fully retain there is approximately equal to the time spent on the current or direct flow capillary imbibition of this heterogeneity with the rest layer. Let us now compare the rate of "replacement" of oil in a block with water when cyclically acting on a formation with the speed of countercurrent capillary impregnation, which is expressed by the following formula [11]:

$$\bar{\varphi}(t_*) = \frac{m_2 \cdot S_1 \cdot \sigma \cdot \cos\theta \cdot \sqrt{\frac{k_2}{m_2} \cdot S_y^2}}{\tau \cdot \mu}. \qquad (10)$$

where m_2 is the porosity of rock blocks, 0.2; s_1 is block water saturation, 0.5; σ – surface tension, 34.4 · 10-3 N / m; $\cos\theta$ – wetting angle, 0.6; $\tau = 25.3$, determined experimentally [11].

The value obtained by the formula (10) must be compared with the values of the average fluid flow per cycle by the formula (7) for different frequency of impulses in the fluid. The comparison is shown in Figure 3 with the reduction of the reservoir compressibility over time taken into account.

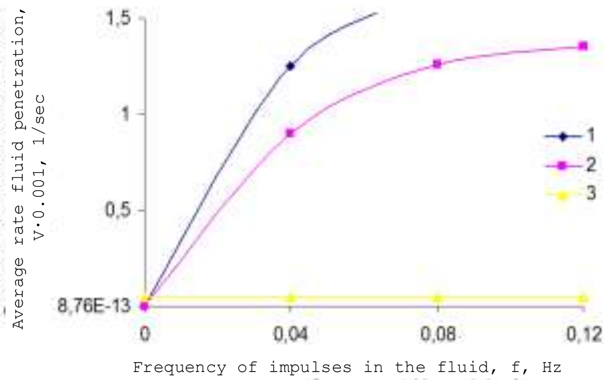

Fig. 3. Graph of the average rate of fluid penetration in the heterogeneity and the reverse capillary imbibition on the frequency of impulses in the fluid: 1 - theoretical rate of fluid penetration in the heterogeneity; 2 - the same with the reduction in the compressibility of the rock; 3 - reverse capillary imbibition rate.

As a result of comparing the parameters, it can be seen that with an increase in the frequency of the pulses in the injected fluid, the rate of reverse capillary imbibition is much less than the rate of incorporation of fluid into the heterogeneity. But we must not forget that an increase in the frequency of pulsations violates the structure of the blocks, due to the presence of mechanical activation processes at high frequencies, thereby reducing the effect of capillary imbibition. Therefore an optimal option of this method consists in the gradual increase in the frequency of the pulsation of the injected fluid.

It can be assumed that the larger the component of the filtration rate along a line parallel to the row of dividing injection wells, the more uniformly the oil will be displaced [12].

Let us consider the area of the reservoir with the wells of the injection and production rows (Figure 4). We choose a coordinate system so that one of the axes coincides with the line of the location of injection wells. For the point M with the x coordinate and the abscissa y of the selected coordinate system, the components of the filtering rate along the axes are V_x and V_y, respectively. Since the direction of the filtration rate component coincides with the location of the injection wells, the efficiency of cyclic flooding will be determined by the magnitude of the increase in V_x from the change in the operating mode of the injection wells. The value of the filtration rate projection on the y-axis, i.e. V_x from changing the mode of operation of injection wells. The value of the filtration rate projection on the y-axis, i.e. $V_x$is analytically determined by the expression

$$V_x = -\frac{K}{\mu} \cdot \frac{dp}{dx}, \qquad (11)$$

where K is the permeability of the reservoir; μ is the fluid viscosity; $\frac{dp}{dx}$ – pressure gradient.

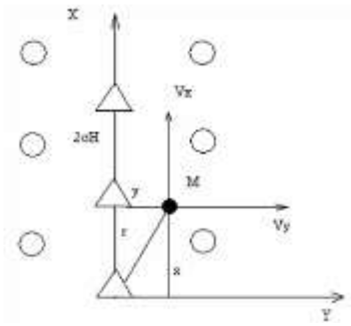

Fig. 4. The design scheme of the field with the wells of injection and production rows: Δ - injection well; O - production well.

The pressure distribution at a point located at a distance r from the disturbance source is determined by an integral-exponential function [13]

$$\Delta P(r,t) = \frac{Q\mu}{4\pi kh}\left[-E_i\left(-\frac{r^2}{4xt}\right)\right], \qquad (12)$$

where x is piezoconductivity of the reservoir.

As $r = \sqrt{x^2+y^2}$, and consequently $dr = \frac{xdx}{\sqrt{x^2+y^2}}$, we obtain

$$V_x = \frac{Q}{2\pi h}\frac{e^{-\left(\frac{x^2+y^2}{4xt}\right)}}{x^2+y^2} \cdot x, \qquad (13)$$

For practical use, it is convenient to present the previous formula as a function of the ratio of the value of the ordinate x to half the distance between injection wells $\sigma_н$ [10].

As a result, we get

$$V_x = \frac{Q}{2\pi h\sigma_н} \cdot \frac{e^{-\frac{\sigma_н^2}{4xt}\left(\frac{x^2}{\sigma_н^2}+\frac{y_н^2}{\sigma_н^2}\right)}}{\left(\frac{x^2}{\sigma_н^2}+\frac{y^2}{\sigma_н^2}\right)} \cdot \frac{x}{\sigma_н}. \qquad (14)$$

Let us introduce the concept of a dimensionless change in the filtration rate along the ordinate [13]:

$$V_x^* = V_x \frac{2\pi h\sigma_н}{Q}. \qquad (15)$$

In order to simplify, we restrict ourselves to the case y = 0. The results of calculating changes in the dimensionless filtration rate for different values $\frac{\sigma_н^2}{4xt}, \frac{x}{\sigma_н}$ are shown in Figure 5. Since the filtration rate and its components along the axes are vectorial values, when choosing an optimal option of non-stationary flooding, it is necessary to take into account direction. From this it follows that for two simultaneously shut-off injection wells in the area between them, the change in the filtration rate along a line parallel to the row of dividing injection wells occurs in opposite directions. Consequently, the absolute value of the final change in speed is determined by the difference in the absolute values of the change in velocity from each of the wells. In the rest of the reservoir, in relation to the specified lane, the mechanism is reverse.

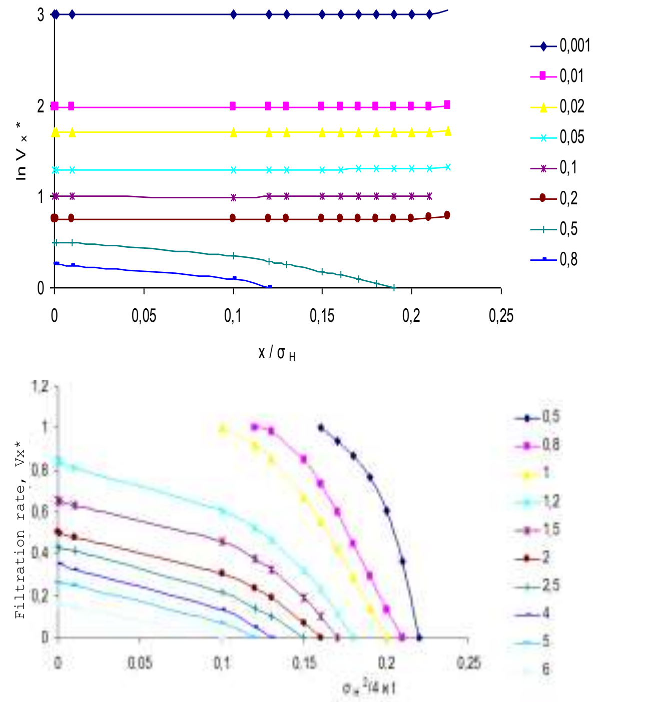

Fig. 5. The dependence of the dimensionless filtration rate V_x^* on the ratio $\frac{\sigma_н^2}{4xt}$ for different values of $\frac{x}{\sigma_н}$.

s an illustrative example of assessing the impact of the order of regime change on the efficiency of changing the direction of filtration, take a section of row of dividing injection wells with four injection wells having the same injection capacity (Figure 6).

Figure 6 also presents diagrams of changes in the dimensionless filtration rate along the line of wells, calculated by the formula (15) [10] with $\frac{\sigma_н^2}{4xt}$ = 0.001; 0.1 – for four shutdown options: 1 - alternately one by one; 2 - all at the same time; 3 - well 1 together with well 3, then well 2 together with well 4; 4 - well 1 together with well 4 - then well 2 together with well 3.

IV. Conclusion

As can be seen, the greatest final effect of changing the filtration rate along the row of dividing injection wells, and, consequently, the effect of impulse non-stationary flooding is achieved by stopping the wells, then the third, fourth and second options follow in decreasing order.

It is important to note that with simultaneous shutdown of injection wells, no closer than one will be involved in active development of the zone between the wells, which are usually prone to stagnation and difficult to produce under continuous flooding. If the neighboring injection wells are in the synchronous phase of the regime change, then there is a danger of formation of stagnant zones. Moreover, analysis of formula (14) implies that in block development systems, the rank sequence of options in terms of the achieved change in filtration direction is preserved for the general case y = 0, also heterogeineus and flooded reservoir, since not its parameters, but the direction of change in fluid movement from each wells determines the final effect.

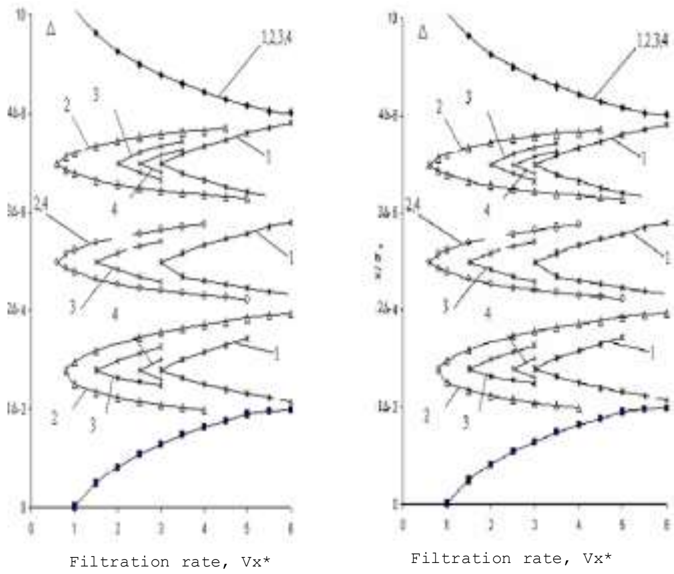

Fig. 6. Diagrams of the change in the dimensionless filtration rate V_x^*, respectively, at 1, 2, 3, 4 options for stopping injection wells.

The maximum distance between injection wells, the mode of operation of which can vary simultaneously, is limited by the duration of the shutdown and subsequent injection of water. In fractions of 2σ_н (rounded to a smaller integer), this maximum distance will be defined as the ratio of the duration of a full cycle to the length of the smaller half-cycle. So, if the duration of half cycles is the same, then this ratio is equal to two, i.e. every second well must be stopped

However, this does not mean that other options for flooding are excluded. The conditions for the development of fields and the advancement of areal limits of oil sand may require a significant change in the direction of filtration in one area and a small change in another. In this case, the sequence of changes in the mode of operation of the wells should take into account the goal. In particular, for the reservoir zone, which is external to the strip between injection wells participating in a one-time stop, the changes in filtration direction from each well, as noted, are summarized. Therefore, for all points of the reservoir that are beyond the limits of the location of the extreme simultaneously stopped injection wells, stopping all the nearest wells can create a more powerful amplitude instantaneous change in the direction of filtration than when they are stopped on the principle of one.

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