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TOPICAL ISSUE

Wave and Physical-Chemical Methods for Managing the Development of Oil Fields with Anomal Reserves

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Abstract—When extracting oil from reservoirs, the use of active physical and chemical reagents in combination with high-frequency wave oscillations as control actions leads to an increase in the oil recovery factor due to the involvement in the process of displacement of reserves that cannot be recovered by traditional flooding (with the injection of water into injection wells). The article presents results of numerical experiments using a mathematical model of cylindrical waves in the direction of the filtration flow of fluids; the effectiveness of cyclic control wave influences is shown. Complex problems associated with the application of hydrodynamic methods to weakly discontinuous vibrations in an inhomogeneous medium are noted and ways to resolve these probltms are indicated. It is shown that the proposed combined methods of control influences on the process of filtration displacement of anomalous and difficult-to-recover oil fractions from oil-saturated porous media of natural deposits provide an increase in the final oil recovery factor by potentially 10–15%.

Keywords: anomalous and hard-to-recover oil reserves, active physical and chemical reagents, cyclic control actions, cylindrical weakly discontinuous pressure waves, mathematical model of the process

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1. INTROCUCTION

The efficiency of extracting anomalous (high-viscosity) and difficult-to-recover (trapped in low-permeability formations and/or supported on the walls of pores and cracks by capillary forces and/or adhesion forces, etc.) oil reserves from natural deposits using traditional methods is unsatisfactory. With this approach to field development, residual (unrecovered) oil reserves reach an average of 55–75% of the original geological ones. Therefore, the problem of increasing the efficiency of development of natural deposits with anomalous and difficult to recover is extremely relevant and in order to achieve the highest oil recovery factor of natural deposits it is necessary to use modern technologies of active control influence on the process of filtration of fluids (oil, gas and aqueous solutions of active reagents) in porous media of field reservoirs. To extract abnormal oil reserves, use active control actions at all stages of development, and to extract hard-to-recover residual reserves at the final stages. Physico-chemical effects in porous media saturated with fluids lead to changes in the properties of formation water and interfaces (boundaries) between water, oil and rock, to a decrease in the relative mobility of water and oil, which leads to alignment of the displacement front and contributes to increased oil recovery and increased displacement coverage of formations and oil recovery factor of deposits. The article proposes a general approach to solving the problems of isothermal displacement of anomalous and difficult-to-recover oil using the following highly effective options for actin reagents listed below (see [1–6]), in particular, displacement of oil with aqueous solutions of active reagents:

1. *Surfactants (surfactants).* When oil is displaced by aqueous solutions of surfactants, the surface tension at the oil-water interface decreases and the mobility of oil increases, which improves its displacement by water. In addition, by improving the wettability of the rock, water is absorbed into the pores occupied by oil, which evens out the displacement front. Polymers. When displaced by polymers, a high molecular weight chemical reagent is formed — a polymer (polyacrylamide), which, even at low concentrations, significantly increases the viscosity of water, reduces its mobility and, as a result, increases the coverage of formations by displacement. Water thickening leads to a corresponding decrease in the ratio of oil and water viscosities in the formation, which leads to worsening conditions for water breakthrough due to formation heterogeneity. The polymer solution preferentially penetrates into highly permeable layers, which leads to equalization of the dynamic heterogeneity of fluid flows and ensures complete coverage of the formations by displacement.

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3. *Alkalis.* During alkali displacement, alkalis interact with oil and rock. When alkali comes into contact with oil, it interacts with organic acids, resulting in the formation of surfactants that reduce interfacial tension at the interface between the oil and alkali solution phases and increase the wettability of the rock with water, which leads to an increase in the coefficient of oil displacement by water. due to washing away highly viscous deposits and oil films held on the surface of cracks and pores.

4. *Carbon dioxide* (CO_2). When carbon dioxide is dissolved, the viscosity of water increases slightly (with a mass content of CO_2 in water of 3–5%, the viscosity of the mixture is only 20–30%), and the resulting carbonic acid H_2CO_3 dissolves some types of cement and formation rock, which increases its permeability. Moreover, carbon dioxide reduces the swelling of clay particles and is four to ten times more soluble in oil than in water, so it can pass from aqueous solution into oil and the interfacial tension between them becomes so low that displacement approaches miscibility. Due to this, high-viscosity deposits and oil films retained on the surface of cracks and pores are washed away and the phase permeability of oil increases. In addition, when CO_2 is dissolved in oil, the viscosity of the oil decreases and the density increases, which makes the main contribution to the displacement of high-viscosity oil by reducing its viscosity. At a pressure above the pressure of complete mixing of oil with CO_2, carbon dioxide will displace oil as an ordinary solvent and three zones will form in the reservoir: the zone of the initial reservoir oil, the transition zone (of oil and the injected active reagent) and the water zone.

5. If CO_2 is injected into a flooded reservoir, then a shaft of oil is formed in front of the CO_2 zone, displacing formation water. Thus, an increase in the volume of oil under the influence of CO_2 dissolving in it, along with a change in the viscosity of liquids (a decrease in the viscosity of oil and an increase in the viscosity of water) is one of the main factors determining the effectiveness of its use in oil production processes at the late stage of field development.

6. *Compositions of active reagents.* The highest priority should be given to micellar-polymer oil displacement, proposed by American scientists, which makes it possible to resume the development

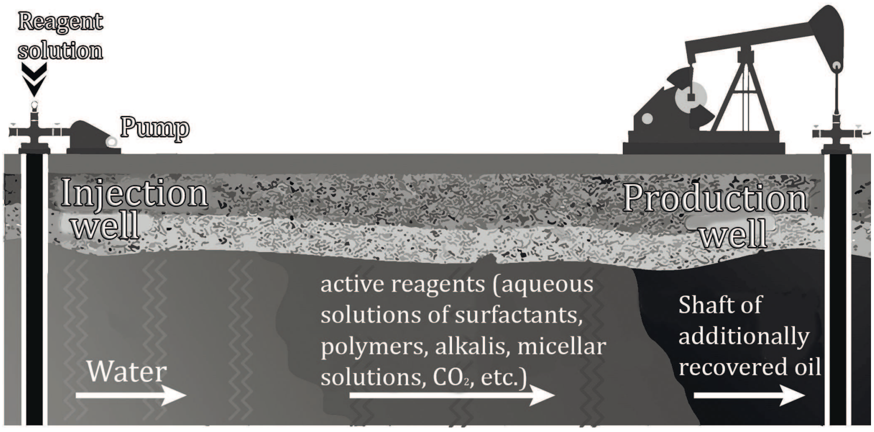

Fig. 1. Filtration flows of active reagent and water slugs.

of a completely watered field. Experiments conducted in the USA have shown that injection of micellar solutions (MS) in the amount of 10% of the pore space makes it possible to extract up to 60When injecting micellar-polymer solutions, the process of oil displacement is carried out by MR slugs, propelled first by the polymer solution and then by water. Typically, such a solution consists of micelles (microassociates) or clumps of water- and oil-soluble surfactants capable of absorbing large amounts of water (up to 80% of the solution volume). In this case, oil remains the external phase (dispersed medium) and, therefore, MR is able to mix in a porous medium (without forming interfaces and menisci) with oil, despite the content of a large amount of water in it. With an increase in the internal phase in the MR, the micelles increase in size, which leads to phase reversal: the MR with the external oil phase goes into solution with the external aqueous phase, which mixes well with water. The composition of MR includes hydrocarbon liquid, water and surfactants of various compositions, including alcohols. When moving them through the formation with high-viscosity polymer solutions, the viscosity of which allows the use of slugs of smaller volumes. The miscibility of MR with water and oil, as well as the fairly low surface tension at the interface between MR and oil and water, create favorable conditions for displacing oil due to the virtual zeroing of capillary forces.

With all of the listed methods for displacing anomalous and hard-to-recover oil reserves, successive filtration flows of slugs of active reagents and water are formed, shown in Fig. 1.

Consequently, to create non-stationary models of the above displacement methods, one can use solutions of initial boundary value problems for the generalized Buck-Lee-Leverett equations, taking into account the distribution of the balance of fluid concentrations with embedded harmonic control actions, also determined by the solutions (corresponding to the method under consideration) of the generalized KdV equation — Burgers. The paper presents the results of a study of optimization of the first of the methods described above through the use of wave control actions in combination with cyclic injection of a sequence of slugs of solutions of surfactants and water. With this effect, the surface tension at the phase boundaries (oil rim, surfactant solution and water) decreases, the mobility of oil fractions increases (improves their displacement by water fractions) and the wettability of the rock (water fractions are absorbed into the pores occupied by immobile oil trapped in small pores), and the total result of these impacts aligns the displacement front, which contributes to the complete extraction of oil from fields with anomalous and difficult-to-recover reserves. Pulsed wave effects accelerate these processes due to intensive mixing and separation of oil fractions with abnormal viscosity, held by adhesion and capillary forces on the surface of the pore walls, which increases their permeability by cleaning the pores and even contributes to the involvement in the process of extracting trapped oil from stagnant zones.

2. MODEL OF THE DIFFUSION PROCESS

High-frequency wave vibrations accelerate diffusion and lead to the intensive erosion of the sharp boundaries between the water and the solvent, as well as between the solvent and the viscous oil; and the liquefaction process occurs in more distant (relative to the axis of the emitter) layers of oil. As a first approximation, we may consider the following model, which describes the change in the viscosity of the mixture in the working space.

$$\varepsilon(x,t) = \frac{(\varepsilon_1+\varepsilon_2)}{2} + \frac{(-\varepsilon_1+\varepsilon_2)}{2}\tanh(e^{-\alpha t}(x-x_0-\beta t)). \tag{1}$$

Here: t is time, x is distance from the emitter axis, ε_1 is the water viscosity coefficient, ε_2 is the oil viscosity coefficient, α is the diffusion rate coefficient (linearly depending on the frequency of wave action), β is the displacement speed (depending on the impact amplitude), x_0 is the initial distance of the interface from the emitter axis. Note that we neglect the initial thickness of the solvent layer. In the process, over time, the viscosities of the mixture components are equalized.

This is illustrated by Figs. 2 and 3. They show change in viscosity in accordance with the formula (1); from left to right the moments $t = 0$; 4; 8; 12; 16; 20 are shown.

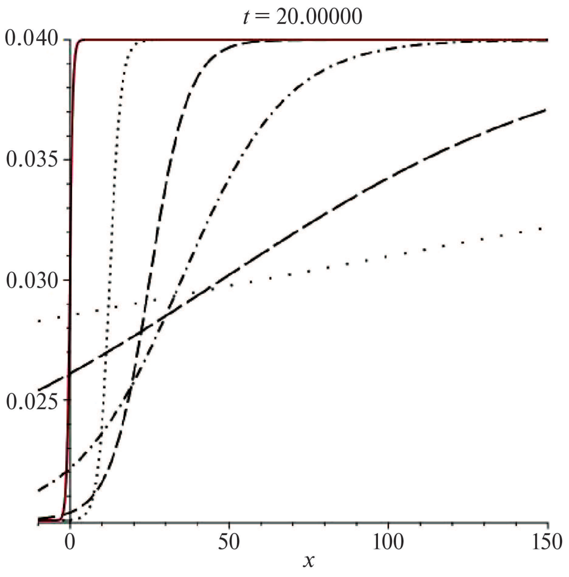

Fig. 2. Dynamics of viscosity for $\varepsilon_2 = 0.04$, $\varepsilon_1 = 0.02$, $\alpha = 3$, $\beta = 0.3$, $s = 5$.

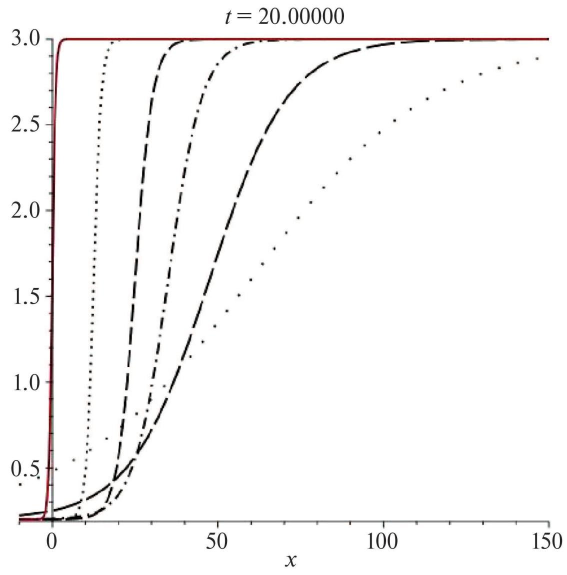

Fig. 3. Dynamics of viscosity for $\varepsilon_2 = 3$, $\varepsilon_1 = 0.2$, $\alpha = 3$, $\beta = 0.2$, $s = 0$.

It is important to understand that the evolution of the diffusion process and the shape of the working zone described here are a priori (albeit plausible). This model is subject to refinement using the theory of fluid filtration in porous media and numerical experiments.

3. QUALITATIVE PICTURE OF THE PROPAGATION OF HARMONIC VIBRATIONS IN A VISCOUS MEDIUM

High-frequency sinusoidal wave effects, including ultrasound, are of greatest interest for oil production practice, [7, 8]. Let us consider (against the background of constant displacement pressure) a traveling concentric wave emitted by a vertical generator and initially having a sinusoidal shape in a medium with viscosity and thermal conductivity. If the intensity of the wave is high enough, then as the wave propagates its shape changes due to several factors. Firstly, it is the geometric factor (due to an increase in the radius of the wave front). In addition, the sinusoidality is deformed due to nonlinearity — the difference in speeds of sections of the wave profile of different heights. Points under greater pressure move faster. As a result, the steepness of the wave fronts increases, and weak discontinuities may appear instead of smooth extremes. The wave takes on a sawtooth shape. However, no real discontinuities occur: the influence of viscosity and thermal conductivity leads to a smoothing of the wave profile and a decrease in velocity and temperature gradients. Therefore, when a sinusoidal wave (near the generator) propagates, the steepness of its front increases until the influence of nonlinear and dissipative factors is compensated. The wave shape is stabilized (up to the geometric divergence of the concentric propagation process).

After stabilization, the wave shape continues to change: the amplitude attenuation leads to a decrease in the influence of nonlinear effects, and the wave profile gradually smoothes out, first again acquiring a quasi-harmonic shape with the original frequency while the amplitude of the sinusoidal component tending to a constant. In the problem under consideration, waves propagate in a relatively thin layer of the deposit from a small vibration source and, therefore, have a cylindrical shape.

The propagation of cylindrical waves of amplitude is similar to the process of propagation of plane waves. As there, nonlinear phenomena cause a change in the shape of the propagating wave and can lead to the appearance of weak shocks and intense absorption. The differences manifest themselves, however, in a different growth rate of nonlinear distortions during the propagation of cylindrical waves, which is caused by a change in the amplitudes of such waves due to their geometric divergence. To describe the propagation of cylindrical waves of finite amplitude, the system of hydrodynamic equations and the equation of state are reduced (without taking into account dispersion) to one approximate equation of the form

$$a\frac{\partial v}{\partial r} + \frac{v}{2r} - \frac{\varepsilon}{c_0^2} v \frac{\partial v}{\partial y} = a\frac{\partial^2 v}{\partial y^2}. \tag{2}$$

Here $= t - r/c_0$, $\varepsilon = (\gamma + 1)/2$, r is the distance to the emitter and c_0 is the signal speed in the medium; k is the wave number. Note that this equation is applicable only in the case of $kr \gg 1$, $y = t - (r - r_0)/c_0$. After changing variables, this coincides with the Kortweg-de Vries equation for cylindrical waves. Let us present its dimensionless normalized form:

$$u_t = -2uu_x + \varepsilon(x,t)u_{xx} + u/2t. \tag{3}$$

To account for variance arising from nonlinear effects. an additional term is introduced, which leads to the Kortweg-de Vries–Burgers equation for cylindrical waves:

$$u_t = -2uu_x + \varepsilon(x,t)u_{xx} + u/2t + u_{xxx}. \tag{4}$$

Here u is the reduced value of the disturbance. The initial boundary problem looks like this:

$$u(x,0) = a, \quad u(0,t) = a + b\sin(kt), \quad u(L,t) = a, \quad u_x(L,t) = 0, \quad L \gg 0. \tag{5}$$

Here a is the displacement caused by constant displacement pressure, b and k are the amplitude and frequency of the wave action. For $t \gg 1$, equation (4) tends to the flat Kortweg-de Vries-Burgers equation;

$$u_t = -2uu_x + \varepsilon(x,t)u_{xx} + u_{xxx},$$

the same thing happens with his decisions.

4. NUMERICAL MODELING

We have carried out numerical modeling of the displacement of residual oil from the reservoir using surfactants, taking into account wave effects in accordance with the models described in Sections 2 and 3. In Figs. 4 and 5 show the zone of penetration of wave influences simultaneously with the dynamics of the viscosity coefficients in the case of $\varepsilon_1 = 0.1$, $\epsilon_2 = 5$, $\alpha = 2$, $\beta = 0.002$; $x_0 = 0$, i.e.

$$\varepsilon(x,t) = 2.55 + 2.45\tanh(e^{-0.002t}(x - 2t)).$$

The wave action initially has a harmonic form $u(0,t) = 3 + 2\sin(5t)$. The specific numbers in this example are not tied to any real deposit or surfactant characteristics. We are interested, first of all, in the fundamental effect of control wave influences. However, a 50-fold increase in the viscosity of oil compared to water seems plausible.

As can be seen from the graphs of numerical solutions, the harmonic shape is transformed into a sawtooth weakly discontinuous shape and then decays to a stable shock wave. The attenuation ends in the vicinity of the largest viscosity coefficient gradient at the interface between water and residual oil. In this zone, all the energy of the sinusoidal component of the harmonic is spent. The further propagation of the monotonic convex shape of the shock wave is explained by the presence of a constant harmonic component; its speed corresponds to the speed of sound in a viscous medium.

For a cylindrical wave, the shape of this monotonic section up to the shock front of the section is given by the formula

$$u(x,t) = \frac{V}{3}\left(2 + \sqrt{\frac{(4-3x)}{\sqrt{t}}}\right),$$

as shown in [9]. Here V is the speed of sound corresponding to the amplitude in a medium with quadratic nonlinearity.

In Figs. 4–7 the solid line corresponds to the amplitude of the wave action, and the dotted line corresponds to the viscosity distribution depending on the distance from the axis of the oscillation generator; the figures correspond to successive moments of time $t = 5$, 11, 18 and 25.

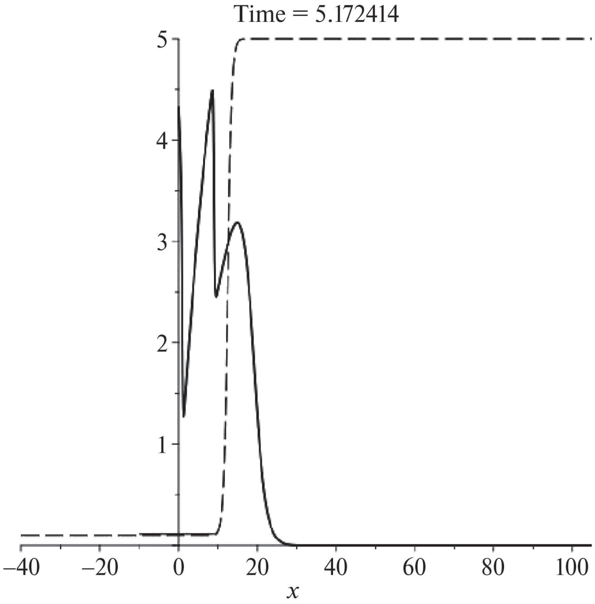

Fig. 4. Joint dynamics of wave effects and surfactant rim; $t \approx 5$.

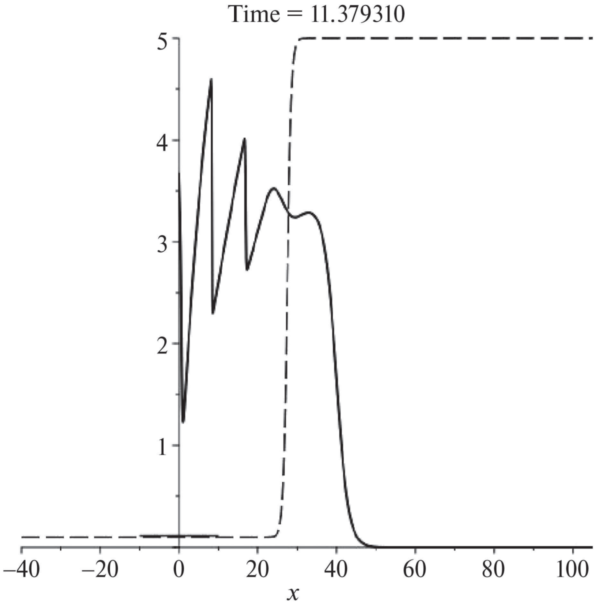

Fig. 5. Joint dynamics of wave effects and surfactant rim; $t \approx 11$.

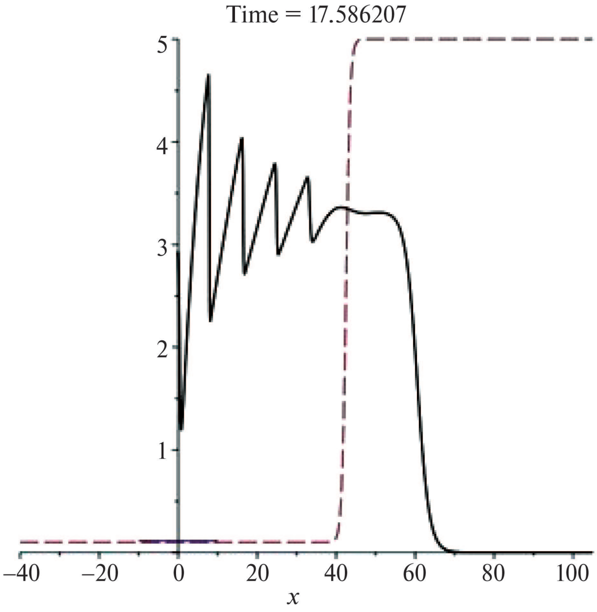

Fig. 6. Joint dynamics of wave effects and surfactant rim; $t \approx 18$.

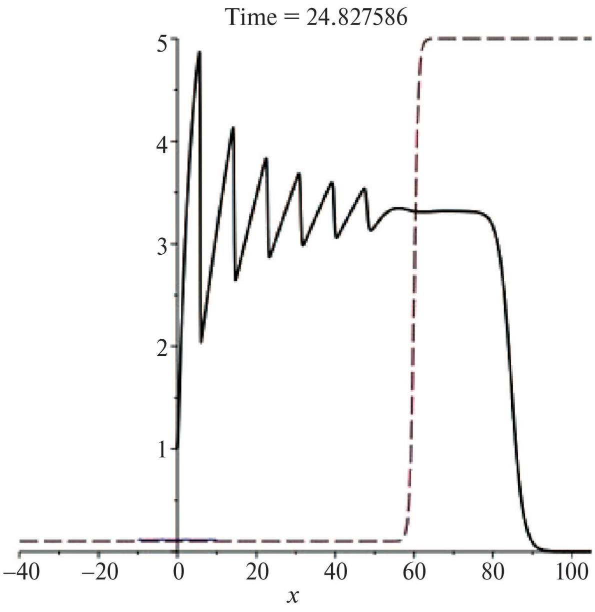

Fig. 7. Joint dynamics of wave effects and surfactant rim; $t \approx 25$.

Based on the analysis of the graphs presented in Figs. 4–7, we can conclude about the effectiveness of wave effects in the method of displacing residual oil using a surfactant. By choosing a suitable initial harmonic, the wave effect can be brought to the interface between the surfactant solution and oil, where the oscillation energy will be completely spent on the process of their mixing and, due to the complex effect, will increase the concentration of additional oil in the filtration stream of the produced product.

To assess the effectiveness of the proposed approach, it is necessary to estimate two parameters of the control wave action. The specificity of the corresponding scientific problems is that the environment in which the process occurs is highly heterogeneous (water-transition layer-oil), and obtaining accurate analytical solutions seems to be an unrealistic task. At the first stage of research, numerical experiments are inevitable. and only later the full-scale ones can be used.

From a practical point of view, the dependence of the penetration range on the source of oscillations of the nonlinear wave (its effective working part) on its amplitude and frequency, as well as on the hydrodynamic properties of the medium, is vost important. Similar estimates can be found in the literature, but only for a homogeneous medium. Thus, the position of the cylindrical wave discontinuity is determined by the following condition

$$2\sigma_0|\sqrt{r/r_0} - 1| = 1,$$

where $\sigma = rMk\varepsilon$ is the dimensionless distance, M is the Mach number. An estimate of the propagation range of a sawtooth waveform is given by the formula, see [7]

$$\sigma_{fin} = \pi^2/2\Gamma, \quad \Gamma = 2\varepsilon\sigma \times Re.$$

It should be noted that these estimates refer to a homogeneous medium and are subject to clarification in the case of a three-component medium: water-active reagent-anomalous oil.

5. MECHANISM OF WAVE PROCESSES OF OIL DISPLACEMENT BY ACTIVE REAGENTS

The high efficiency of wave processes of oil displacement by active reagents is determined by the following circumstances.

At large amplitudes of oscillations, stationary flows, or acoustic flows, arise in liquids. These flows are especially pronounced near obstacles of various kinds located in the impact zone. They always have a vortex character. The speed of these flows increases with increasing intensity, but even at the highest intensities it remains less than the vibrational speed in the wave, [10].

As is known, flows are caused by constant forces, the magnitude of which can be estimated taking into account nonlinear effects. A large number of publications are devoted to acoustic flows, [10].

From the point of view of the possibilities for more complete extraction of oil reserves, boundary currents near the surfaces of bodies in contact with the oscillation field are of particular interest. These flows, disturbing the boundary layer, explain the acceleration of transfer processes under the influence of vibrations: heat transfer of heated bodies, changes in concentration when cleaning contaminated surfaces, and the like. Acoustic stimulation is an effective method for perturbing the boundary layer.

The following types of acoustic flows are important for the problem under discussion: The first is flows outside the boundary layer, which also have a vortex character. The scale of these vortices is significantly larger than the scale of the boundary layer vortices. One type of flow of this type is a two-dimensional flow between two planes, arising under the action of a wave; the vortices in this case have a scale equal to the length of the sound wave. In the proposed approach, such vortices should contribute to the mixing of components inside the working area.

The second is the flows that arise in the viscous boundary layer near the upper and lower boundaries of the reservoir. It is known that under the influence of high-frequency oscillations, stationary flows in the boundary layer have a vortex character. The scale of these boundary vortices, as a rule, is determined by the thickness of the acoustic boundary layer; their size is much smaller than the wavelength. In the approach proposed by the authors of the article, these vortices will clear the boundaries of the oil-bearing layer from films and droplets stuck in the pores of the boundary. For these residues on a rigid surface, the velocity gradient is normal to the surface and, of necessity, large in the transition to the general flow in the layer. This leads to oil separation from the walls.

The dynamics of the boundary layer when a wave passes in the x direction is described by the Prandtl equations

$$\frac{\partial v_1}{\partial t} + v_2\frac{\partial v_1}{\partial x} - \nu\frac{\partial^2 v_1}{\partial y^2} = \frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x}, \quad \frac{\partial v_1}{\partial x} + \frac{\partial v_2}{\partial y} = 0. \tag{6}$$

Here v_1 and v_2 are the x and y components of the velocity, $U(x,t)$ is the known flow velocity away from the boundary. Note that for a sawtooth wave $\frac{\partial U}{\partial x}$ is discontinuous.

Known estimates for the speed v, for example see [10], obtained in the case of sinusoidal oscillations U, are hardly applicable. However, it is quite obvious that at weak discontinuities the absorption of energy increases and the velocities of the vortices increase. An analytical solution to equation (5) is not available. Approximate solutions are obtained by the perturbation method, but in the case of sawtooth waves, the use of numerical modeling methods is inevitable.

To implement the proposed technologies, it is necessary to use a triangular layout of injection and production wells (see Fig. 8), and it is advisable to carry out wave impacts in injection wells sequentially through one. In this case, the choice of the duration of the wave action intervals and the volumetric dimensions of the active reagent fringes will be additional control means, see Fig. 8.

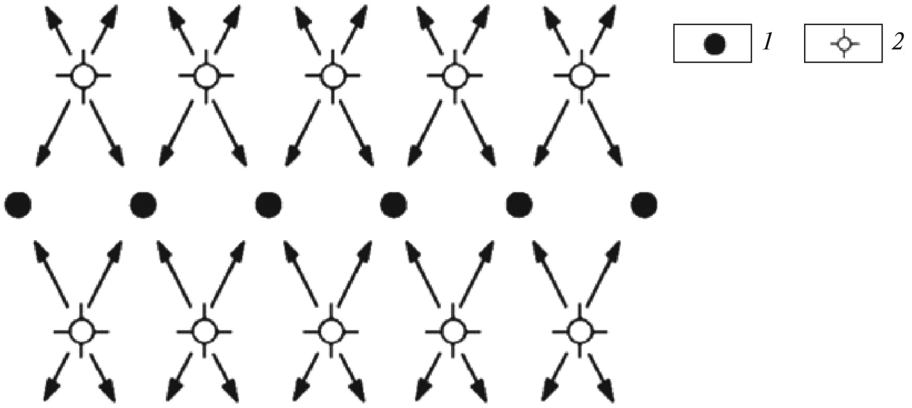

Fig. 8. Layout diagram of production (*1*) and injection (*2*) wells.

The proposed research results can be used without any particular difficulties to create models of flows of heterogeneous fluid mixtures in porous continuous media saturated with abnormally viscous oil, when there is a monotonic increase or decrease in filtration resistance, i.e. pseudoplastic or dilatant flows are described by Forchheimer's power and three-term filtration laws [6].

6. CONCLUSION

The article discusses the extraction of hard-to-recover oil reserves using active reagents; high-frequency wave oscillations accelerate diffusion and lead to intensive alignment of the displacement front due to smoothing of the interface between water and the active reagent and is accompanied by equalization of the filtration parameters of fluids (oil, water and active reagents) in the flow, which helps to increase the oil recovery factor (oil recovery factor) of reservoir layers.

The use of high-frequency wave oscillations accelerates diffusion and leads to the intensive eroding of the sharp boundaries between the water and the solvent, as well as between the solvent and the viscous oil; and the liquefaction process occurs in more distant (relative to the axis of the emitter) layers of oil. We have studied a qualitative picture of this process.

If the intensity of the wave is high enough, then as it propagates its shape changes due to several factors.

Firstly, this is a geometric factor (a consequence of an increase in the radius of the wave front). Secondly, the sinusoidality is deformed due to nonlinearity — the difference in speeds of sections of the wave profile of different heights. Points under greater pressure move faster. As a result, the steepness of the wave fronts increases, and weak discontinuities may appear instead of smooth extremes. The wave takes on a sawtooth shape. When an initially sinusoidal wave propagates further, the steepness of its front increases until the influence of nonlinear and dissipative factors is compensated. The wave shape is stabilized (up to the geometric divergence of the concentric propagation process).

After stabilization, the wave shape continues to change: its profile gradually smoothes out, first again acquiring a quasi-harmonic shape with the original frequency and the amplitude of the sinusoidal component tending to a constant. At this stage, the energy of control oscillations is completely transferred to the medium in which chaotic thermal motion occurs.

We conducted numerical experiments using a mathematical model of the process for cylindrical waves in the direction of the filtration flow of fluids. Based on these calculations, we can draw a conclusion about the effectiveness of wave effects in the method of displacing residual oil using surfactants. By choosing a suitable initial harmonic, it is possible to bring the oscillation energy to the boundary zone between water and oil, where it is completely spent on mixing oil and surfactants and, thereby, increases the involvement of oil in the solution and the speed of the process.

The article highlights complex problems associated with the application of hydrodynamic methods to weakly discontinuous vibrations in an inhomogeneous medium and indicates ways to resolve them.

Since when using all types of active reagents (solutions: carbon dioxide, surfactants, alkalis, polymers, etc.), the mechanism of wave processes for displacing hard-to-recover oil reserves is identical, you can be sure that similar studies will confirm the effectiveness of cyclic control wave actions in the injection interval of active reagents to increase oil recovery from natural deposits. The use of wave effects using a combination (thermal, physical-chemical, etc.) of active reagents will lead to greater efficiency in the process of displacing hard-to-recover oil reserves and a significant increase in oil recovery.

The results proposed in the article are a further development and generalization of the methods presented in the article [11].

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