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OIL PRODUCTION INCREASE DUE TO FORMATION STIMULATION WITH THE HELP OF MECHANICAL OSCILLATIONS TRAIN

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Abstract. *One of the promising areas of research in improving oil recovery from reservoirs is the study of influence of mechanical oscillations train. Studies of the effect of mechanical oscillations in the tight oil zones for increase of oil recovery rate are at their early stages. Aim of this paper is the theoretical and experimental research of the mechanical wave effect at different frequencies on oil-water mixture filtration in the borehole zone and interwell zone, which results in increase of oil well productivity and oil recovery factor at oil fields.*

Keywords: *mechanical oscillations, filtration, oil, frequency, intensity*

In the recent years, oil and gas industry specialists are interested more and more in practical use of new highly efficient and cost-effective technologies for stable growth of oil production in complex geological and industrial environment. During the development of oil fields, reservoir pressure decays and at a certain stage of field development the existing reservoir energy is insufficient to displace oil from tight zones to the producing well, which results showing of no flow (low-moving) oil zones. In irregular permeability reservoirs during oil displacement by water, the conditions for blocking oil in less permeable reservoir zones are established and, consequently, it causes increase of water flow to the wells, which leads to decrease in oil recovery.

One of the promising areas of research in improving oil recovery from reservoirs is the study of influence of mechanical oscillations train.

Main part of the theoretical and experimental researches, described in literature, concerns the study of the effect of mechanical oscillations in porous borehole zones.

Studies of the effect of mechanical oscillations in the tight oil zones for increase of oil recovery rate are at their early stages.

Interaction mechanisms of the mechanical wave field with porous oil-water saturated layers at filtration of oil-water mixture in the oil reservoir are not enough surveyed. Firstly, those are the mechanisms of mechanical wave influence on speed of fluid filtration in porous formations.

Aim of this paper is the theoretical and experimental research of the mechanical wave effect at different frequencies on oil-water mixture filtration in the borehole zone and interwell zone, which results in increase of oil well productivity and oil recovery factor at oil fields. The studies were accomplished in Ivano-Frankivsk National Technical University of Oil and Gas and scientific-production company "Inteks".

Influence on borehole zone.

Let us give consideration to the impact of mechanical vibrations in the borehole zone in order to increase productivity of oil wells, involving the concepts of pressure gradients. Pressure gradients in the borehole zone are produced by well or ground hydraulic generator of mechanical waves.

Analysis of the processes of mechanical vibrations influence the in borehole zone, involving the pressure gradient, is appropriate due to the fact that we consider the processes taking place in the borehole and formation zones with linear dimensions not exceeding the wavelength of mechanical waves with frequencies from a few to several thousand hertz. For example, in [1 - 3], a sharp decrease in permeability in the borehole zone is observed at distances of several centimeters up to 1.5 - 2.0 m.

In this study, the pulsed mode of operation of hydraulic generator is considered, which creates pressure pulses in a liquid medium wells.

Pressure hydro-pulse, acting with a certain repetition rate for surrounding the well layered medium (water-steel-cement-reservoir), excites trains of damped mechanical oscillations of a certain duration in the formation.

Parameters of wave trains (the maximum range of the oscillations in the train, its duration) are defined as the acoustic characteristics of the reservoir (quality factor, the propagation velocity and absorption factor of the mechanical vibrations, the acoustic impedance), and sequence parameters hydro-pulse pressure (range, pulse repetition frequency). When the train repetition rate increases, duty ratio of the train sequence (correlation of the repetition period to the train duration) decreases [4].

So the research results, presented in [5], show that the influence of mechanical pressure pulses on sandstone with the intensity of 90 W/cm^2, wave trains appear in the reservoir in spectral decomposition of which are dominated by harmonic components in the frequency range 20 - 1000 Hz and the duration of the package is on average 0.1 s. Thus, when the train repetition frequency is 10 Hz, the duty ratio of the train sequence is equal to one.

Proceeding from the values of the frequency spectrum, the velocity of acoustic waves in borehole and reservoir area, and as a result the length of acoustic waves in these environments, the characteristic geometric dimensions of environment where we are interested in the effect of mechanical waves on a layer, it is possible, as noted in [1], to use non-wave analysis methods based on the concept of pressure gradient grad p:

$$\text{grad } p = \frac{dp}{dt} \approx \frac{\Delta p}{\Delta t}, \qquad (1)$$

where Δp – pressure difference between two single-site environments (isotropic and regular in the chosen direction), which are separated from each other at distance of Δl.

While operating the well, esp. during the filtration process when various types of colmatated particles get into the borehole zone, the formation fluid turns into the colloid-dispersed structure (CDS), which is a non-Newtonian fluid, in the borehole zone

[1, 6, 7]. The denoted liquid creates a significant pressure drop in fluid motion, causing fall of well production. To begin non-Newtonian fluid motion in the reservoir pores, the breaking pressure gradient can be estimated using the following inequality [1, 6]:

$$\text{grad } p > \frac{\tau_0}{K_{np}^{1/2}}, \tag{2}$$

where τ_0 – breaking effort shift, which corresponds to the minimum static pressure drop, causing the destruction of the spatial grid CDS; K_{np} – factor of permeability.

In our case, pressure varies over time. This change in pressure (as well as pressure front) moves in the environment with velocity C_m of acoustic wave propagation in this medium (physics of these phenomena is the same). During the Δt of the mechanical wave front pressure Δp travels along distance Δl at C_m, so we obtain:

$$\text{grad } p = \Delta p / \Delta l = \Delta p / (C_n \Delta t) = (\Delta p / \Delta t) : C_m . \tag{3}$$

The velocity of mechanical waves propagation in the environment with C_m is a constant value which is determined by physical parameters of the medium, in this case – the reservoir. The numerator of (3) is equal to the rate of pressure change over time. According to the theory of harmonic analysis [8, 9, 10] the shorter the fronts of pulse processes, the greater the amplitude of higher harmonic components of pulse processes decomposition. It follows that with (3) we can get the same pressure gradients, as in the high-action, and at low frequency, but sufficiently large in amplitude (differential pressure).

As mentioned above, low fluid permeability reservoir zone that surrounds the perforated zone of the well, is caused due to the formation of bed CDS, which is a "plug" to the size of the wall thickness of no more than 1.5 - 2.0 m. Under these geometrical dimensions of the "plug" transmission coefficient of the mechanical energy is at 0.6 [2].

Therefore, in the near zone of the reservoir at distance from the borehole wall to several meters, forms of acoustic pressure pulses (wave trains), generated during stimulation of hydro-pulse pressure, change little.

If steep leading edge of the wave packet $dp/dt \approx \Delta p/\Delta t$, by (2) is created throughout the thickness of "plug" CDS, sufficient to create grad p, which causes the destruction of the CDS structure, the non-Newtonian fluid in the borehole zone becomes more fluential and can be displaced into the borehole space. It is necessary to displace the broken structure of CDS formation, since it is able to self-repair [1, 7]. From this perspective, it is expedient to combine the acoustic pulse with the simultaneous action of differential pressure.

Based on the foregoing, we conclude that the analysis of mechanical stress processes on the borehole zone with the concepts of pressure gradients allows us to connect physical and mechanical characteristics of the reservoir bed, formation fluid with the desired values of pressure gradients in the reservoir, created in order to change the characteristics of this system.

Indeed, the expression (2) determines the magnitude of the pressure gradient required for the changes in physical-mechanical characteristics of the plastic fluid. With the knowledge of radius of the modified permeability and pressure gradient, which has to act in this area, we can define the technical parameters of the well pulse pressure generator for individual wells.

To ensure the operation of the pressure gradient along the length of the radius of the modified zone with changed permeability, calculated value of Δl must be greater than the actual value of the radius of the modified zone in permeability R. The value of Δl depends on the amplitude and duration of the leading edge of the pulse pressure, as well as the values of C_m.

The value $\mathrm{grad}\,P$, needed to break ties between colmatant coagulating particles, are determined according to expression (2) for a particular layer from the value of the breaking effort shift τ_0 of reservoir fluid and permeability factor K_{np}.

According to expression (3), the required amplitude of pressure pulses in porous medium layer, can be determined from the assigned values for a particular reservoir $\mathrm{grad}\,P$, the duration of the leading edge of the wave packets Δt, as well as the zone radius of changing permeability R. In first approximation, the duration of the leading edge of the wave packets can be taken as the rise time of the oscillation amplitude in the train between minimum and maximum values, which, with sufficient accuracy for practical calculations, corresponds to the front of hydro-pulse pressure generated by wells pulse pressure generator in the well. The rise time of pressure in the well (the length of the front edge of the pulse pressure) can be determined with high-speed electronic manometer.

R is calculated from the results of hydrodynamic studies of the reservoir based on standard procedures, and duration of the leading edge of the pulse pressure for a given pulse generator accepting not less than the ratio of R/C_m.

After the pulse-wave action creates optimal for specific geological and technical conditions of differential pressure with standard technology and equipment to remove colmatant from borehole zone.

Delay in the establishment depression lead to a re-coagulation colmatant (self-healing coagulation structures) and thus re-locking the borehole zone.

Constructive combination of hydraulic pulse pressure generator and jet pump efficiently cleaned of substances colmatated borehole zone. After the pulse-wave stimulation, using a jet pump selected an optimal values of depression in which the number of substances in the samples of colmatated liquids that are taken on the release of the circulatory system, at regular intervals to be minimal, and the flow of fluid from the reservoir will be stable [11].

Influence on the interwell zone

Investigation of the influence of mechanical waves on filtering oil-water mixtures in the drowning bed, in order to enhance oil recovery from reservoirs, is the subject of many scientific papers [12, 13]. In these papers we study processes of mechanical vibration exposure at seismic frequencies generated by powerful ground-based vibrators on oil reservoirs with formed zones of low fluid permeability. Vibrators are installed on interwell areas in the field and create, on an average depth of the oil formation, the intensity of the mechanical vibrations of less than 0.000001 W/cm^2. Despite the low intensity oscillations obtained industrial results indicate the presence of industry effects using vibroseismic stimulation. Either no or negative effect at determined influence on specific geological and technical conditions is simultaneously observed [13].

As shown in [14], a decrease of capillary resistance to of oil and change rheology of the oil-gas-water fluid under the influence on the formation of mechanical vibrations, is observed when the value of the intensity fluctuations greater than 0.1 W/cm^2.

Given the different estimates of the intensity fluctuations needed to change the filtration processes in formation, the authors formulated the following theoretical and experimental problems in studies of the effects of mechanical waves on the interwell zone :

– to determine on the basis of experimental studies threshold intensity vibrations, within which bed filtration changes appear;

– to determine in terrigenous reservoirs, based on experimental studies, the absorption coefficient of the wave packets are created when a shock load formation;

– a theoretical basis for the establishment in the reservoir at a distance of 100 m the intensity of the vibrations needed to change the rate of filtration in the formation.

This distance is assumed on basis of average distance of 200 - 300 m between injection and production wells and the necessity to install at least two hydraulic pressure pulse generators in the injection wells on the field for effective impact on the tight zones of oil in interwell zones [15].

Experimental studies on the effect of mechanical waves on reservoir model with drowned tight zone of oil were carried through the stimulation of wave-train duration of 0.1 s and a repetition frequency of 1 Hz. In this research qualitative and quantitative impact of mechanical waves on filtering oil-water mixtures in the drowning tight zones of oil was assessed. Studies indicate that the pulse-wave effects on oil-water mixture at its filtration in a porous medium leads to the decrease of capillary resistance to oil in the "oil-water" and, consequently, to improving oil recovery, and the intensity fluctuations in the wave train, where there is a change in the filtration reservoir model, which comprises 0.01 W/cm^2 [16]. At repetition frequency of 1 Hz and train length of 0.1 s, the average intensity can be estimated as $\frac{0{,}01 \cdot 0{,}1}{1} = 0{,}001$ W/cm^2.

Experimental studies to determining the absorption factor of the wave trains in terrigenous reservoirs were carried out with the shock load to the reservoir menilite (argillite) delamination of Bytkovske oilfield.

Experimental tests have shown the ability for appearance of the mechanical vibrations of the wave train with the intensity of 0.1 W/cm^2 at distance of 73 m from the source of vibration with the intensity of the pressure pulse at the point of impact 90 W/cm^2 in menilite surface conditions of reservoir [5].

It was experimentally determined that the damping factor of the wave trains from the impact on the formation of surface conditions in the menilite delamination oil fields is equal to 0.047 m^{-1} [5].

Additional studies, conducted in the same field, in order to clarify the damping factor of the different spectral components of the wave trains, showed that the damping coefficient for the frequency range of 50 - 80 Hz, with the greatest intensity of oscillations is equal to 0.055 m^{-1}. The above is proved by experimental data given in [17] for the surface conditions. In this case, the reservoir conditions according to [17, Table 2.1] accept coefficient $k\lambda = 0{,}63$ dB. Taking into consideration that the 50 Hz frequency of wavelength of terrigenous reservoir is 80 m, the damping coefficient for this frequency is equal to $k = \frac{0{,}63}{80 \cdot 8{,}686} = 10^{-3}$ m^{-1}.

Theoretical studies were conducted in the following areas:

1. Determination of the vibration intensity produced by a hydraulic generator in the well, which is necessary to be obtained in terrigenous collector intensity 0.01 W/cm^2 at distance of not less than 100 m from the generator.

2. Determination of the pressure gradients values, which are created by the passage of the mechanical waves wave trains in reservoir and evaluation of the total pressure gradient, required to change filtration in the reservoir.

The study of acoustic impacts on the interwell zone, to improve oil recovery from reservoirs was conducted with the assistance of the concepts of pressure gradients. This approach is imposed by the fact that the average size of oil field plots, that are in range of downhole generator, should not exceed the wavelength of mechanical waves generated by the generators in the interwell zone.

The following data were taken for the calculations:

– frequency of the wave train is 50 Hz (harmonic spectral decomposition of the wave train with the highest energy vibration) (Figure 2);

– pulse duration t_i is equal to 0.1 s;

– the period of repetition T is equal to 0.1 sec.

In this case, considering that the pulse repetition period is equal to the pulse duration, the intensity value of the wave train of mechanical vibrations I_i will be equal to the average intensity I_c.

Taking into consideration that the lower part of the tube with a hydraulic generator is a linear emitter of mechanical vibrations of considerable length, we accept the first approximation, that this oscillator generates a cylindrical wave.

Therefore, to estimate the intensity fluctuations at the inlet into the formation, which is necessary to obtain the intensity of 0.01 W/cm^2 at distance of 100 m, it is possible to use the expression to determine the changes in the intensity of cylindrical wave with the distance [18]:

$$I_c = \frac{I_0}{x} \cdot e^{-2kx}; \tag{4}$$

$$I_0 = \frac{I_c \cdot x}{e^{-2 \cdot k \cdot x}} = \frac{0{,}01 \cdot 100}{e^{-2 \cdot 10^{-3} \cdot 100}}, \tag{5}$$

where I_0, I_c – respectively, the values of the oscillations intensity of the wave trains sequences of in the input of bed and at 100 m from the well, measured in W/cm^2; k – damping coefficient for the frequency range 50-80 Hz; x – the distance between the points determining the intensity of wave packets in the reservoir, m.

After making all calculations we obtain $I_0 = 1{,}221$ W/cm^2.

To estimate the intensity fluctuations in the well, necessary to create on input into the formation $I_0 = 1{,}221$ W/cm^2, we use the following arguments:

1. Passage of the mechanical waves energy through the casing-cement sheath is very significant, due to the fact that the wavelengths, produced by a hydraulic generator in the casing and cement sheath, are significantly greater than the thickness of layers of metal and cement.

2. As a result, a part of the casing in the area of the hydro-generator is the generator of mechanical vibration, acoustic load which is a saturated reservoir formation (given the proximity of the acoustic characteristics of the cement stone and sandstone reservoir bed).

On the assumption of this and taking into consideration the author's study [2] on the passage of mechanical waves from the borehole zone into the reservoir, we estimate the intensity vibration at the inlet into the reservoir at the level 0.6 of the acoustic output of the generator.

As known, that the power, produced by hydraulic borehole devices, can be determined by the values of pressure drop across the device and the amount of fluid passing through the device at time according to the expression [19]:

$$N = \frac{Q \cdot \Delta P}{600} \cdot \eta, \tag{6}$$

where N – hydro power, kW; ΔP – differential pressure, bar; Q – flow rate required by the hydraulic unit, l/min; η – efficiency of the device.

The maximum pressure drop of the hydro-generator of GKP-56 type, created by "Intex" is 4 MPa at fluid flow rate 340 l/min. Thus, the hydraulic power produced by the generator is 16 kW. If the coefficient of conversion of hydraulic energy to acoustic energy to the generator is known to be 18.3 %, we obtain the acoustic power of the generator equal to 2.93 kW. The inner area of the perforated casing in the zone of maximum intensity of the vibrations, produced by GKP-56, is 350 cmI. The intensity vibration in the borehole, in this case, is equal to 8.37 W/cm I, and the intensity vibration at the inlet into the reservoir, taking into account the loss of acoustic energy in the transition from a liquid medium in the well layer (we assume the transmission coefficient of acoustic energy 0.6 [2]), can be set equal to 5 W/cmI.

These calculations confirm the possibility of creation of hydro-mechanical vibration with the intensity 0.01 W/cm^2 in reservoir at 100 m distance from the borehole.

The results of theoretical and experimental studies show that the effect on the interwell zone should be carried out at much lower frequencies than on borehole zone because of the damping of mechanical waves in porous medium layer. The degree of damping depends on the frequency of oscillations propagating in porous medium layer. Using program SpectraPLUS 5.0 , when comparing the amplitude spectral components of the wave trains at different distances from the point of shock formation, it was established that formation seismic vibrations are damped the least by the frequency range 1-80 Hz in the sandstones . To estimate physical phenomena at distance of more than 2 meters in the porous space of the reservoir during the passage of mechanical waves, it is necessary to take into account the damping spectral of high-frequency components of the wave train and the gradual transformation of the complex wave field generated by wave packets in the borehole zone into field quasi-harmonic mechanical vibrations at low frequencies (Fig. 1).

We define variable pressure gradient generated in the reservoir as a result of the passage of the wave packets of mechanical waves with an average intensity equal to I_c = 0.01 W/cm^2. We accept (Fig. 2) that the main energy component of the wave train is concentrated in the harmonics of 50 Hz. Known from [20], the connection of the intensity and amplitude of the variable pressure $I = P^2 / 2\rho c$, we find pressure gradient, which is formed during the passage of mechanical waves:

$$\text{grad}\, P_D = \frac{4P}{\lambda} = 4\frac{\sqrt{2\rho c I}}{c/f} = f\sqrt{\frac{32\rho I}{c}}\ , \qquad (7)$$

where P – amplitude of the variable sound pressure, Pa; $\text{grad}\, P_D$ – pressure gradient, which is created as a result of the passage of the wave packets of mechanical waves, Pa/m; ρ – average density of the saturated rock, kg/m^3; c – the velocity of longitudinal mechanical wave, m/s; λ – the length of the mechanical wave, m; f – frequency of the harmonics, Hz.

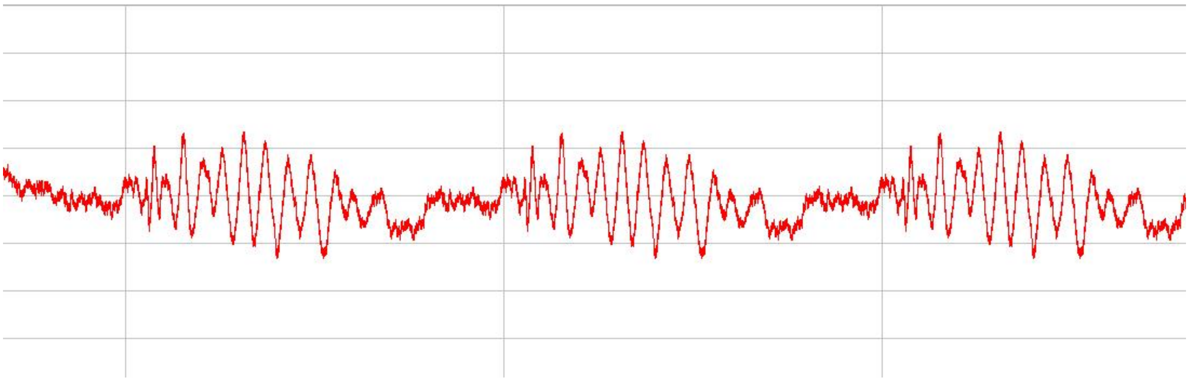

Fig. 1. The sequence of mechanical wave trains at distance of 50 m from the point of shock formation in the program SpectraPLUS

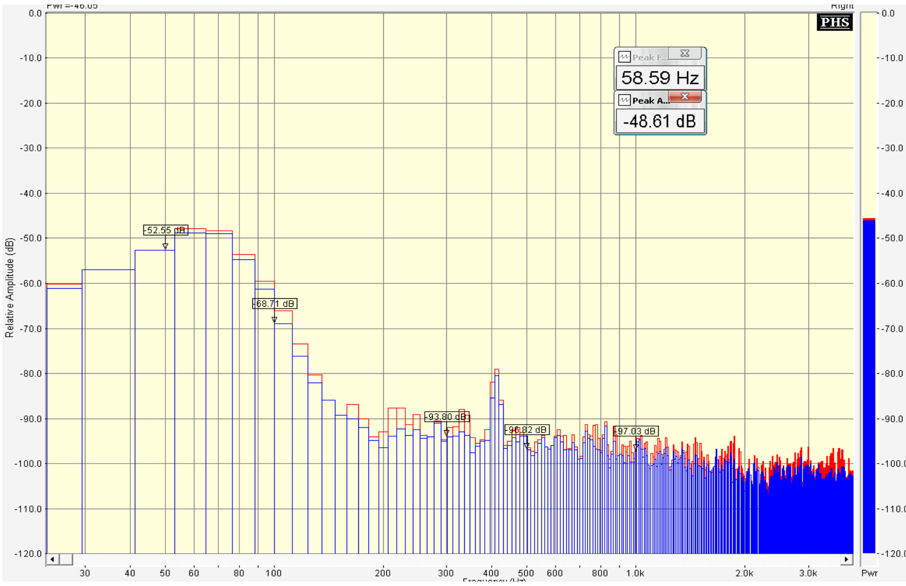

Fig. 2. The spectrum of the mechanical waves train at distance of 50 m from the point of shock formation in the program SpectraPLUS

Taking into consideration that the average density of the saturated rocks $\rho = 2450$ kg/m^3, and the propagation velocity of longitudinal mechanical waves in the skeleton of rocks [2] $c = 4000$ m/s, we obtain the value of variable $\mathrm{grad}\, P_D$ for the harmonics of 50 Hz equal to:

$$\mathrm{grad}\, P_D = 50\sqrt{\frac{2450 \cdot 0{,}01 \cdot 10^4}{4000}} = 2{,}2 \cdot 10^3 \text{ Pa/m}.$$

Studies by Mirzadzhanzade, A.H. showed that when Darcy's law is beyond the scope in the lower boundary, then fluid shows non-Newtonian properties and breaking pressure gradient, which is spent on overcoming the dynamic effort shift for a number of oil fields is in the range 1,2 - 15 kPa/m [21].

Let us estimate the current pressure gradient in the formation in the absence of wave stimulation. Difference between pressure of formation and boreholes pressure assume equal $\Delta P = 5$ MPa, and the distance from the borehole to the external boundary $L = 1000$ m.

In this case, $\text{grad}\, P_C = \Delta P / L = 5 \cdot 10^6 / 1000 = 5 \cdot 10^3$ Pa/m.

Variable pressure gradients in a phase of expansion and contraction phase in the lead to reduce the viscosity of reservoir fluid [14], equivalent to a reduction in the breaking pressure gradient required to overcome the dynamic effort shift τ_0.

Thus, in first approximation, to estimate the total pressure gradient, created in the reservoir during the passage of the wave packet, we can sum the values of variable pressure gradient and current gradient in the reservoir. In our case:

$$\text{grad}\, P_{summ} = \text{grad}\, P_D + \text{grad}\, P_C = 7{,}2 \text{ kPa/m}$$

Hence the total effect of the existing pressure gradient and pressure gradient, generated in the reservoir resulting from the passage of mechanical waves, they overcome the breaking pressure gradient and introduce the development of a significant portion of inactive zones of oil produced in the reservoirs after decreases reservoir pressure.

We estimate the effect of mechanical vibrations on the oil-water contact in the case of the field MRP in the layers of low fluid conductivity zones of oil washed with water reservoir.

Due to the passage of the mechanical waves trains with an average intensity I_c observed in situ compression and tension zones, variable pressure that occurs when this is measured by the known formula [20]:

$$P = \sqrt{2 \rho c I_c}, \tag{8}$$

where P – amplitude of the variable pressure, Pa; I_c – the average intensity of the mechanical vibrations, W/m^2; c – the velocity of longitudinal mechanical wave, m/s; ρ – average density of the saturated rock, kg/m^3.

Overcoming the capillary forces formed at the interface oil-water may in the exercise of inequality $P_к \le P$.

We estimate the amplitude of the variable pressure:

$$P = \sqrt{2 \rho c I} = \sqrt{2 \cdot 2450 \cdot 4000 \cdot 0.01 \cdot 10^4} = 44{,}3 \cdot 10^3 \text{ Pa.}$$

Assuming that the average pore radius of $r = 10$ um, and the surface tension at the oil-water is $\sigma = 27$ mN/m [21], we obtain the value of the capillary pressure [16]:

$$P_к = \frac{2\sigma}{r} = \frac{2 \cdot 27 \cdot 10^{-3}}{10 \cdot 10^{-6}} = 5{,}4 \cdot 10^3 \text{ Pa,} \tag{9}$$

where: $P_к$ – capillary pressure, Pa; σ – surface tension at the oil-water, mN/m; r – the average pore radius, m.

Calculations show that the variable pressure created by the passage of the wave packets can overcome the capillary pressure and bring formation water wash of the oil zone to development.

Based on the foregoing, the most advantageous to the impact on interwell is the use of hydraulic generators with pulse pressure repetition frequency of 1 - 50 Hz, because at distances greater than 2 m from the borehole axis, the main frequencies of mechanical vibrations, which are the least absorbed layer, are the variations in the frequency range 1 - 50 Hz. The intensity of vibrations at the inlet into the reservoir should be not less than 1.2 W/cm^2 to create the filtration change conditions in the reservoir at distances of at least 100 m from the borehole generator.

The calculations show that this intensity can be achieved at pressure difference of 4 MPa and fluid flow of 340 l/min.

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