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A POSSIBLE MECHANISM OF VIBROSEISMIC ACTION ON AN OIL-BEARING BED

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A possible mechanism of the elastic oscillation effect on oil and water filtration is explained. It is shown that liberation of part of the dissolved gas from oil due to vibroseismic action may change phase permeabilities in the oil-water system.

The mechanism of the elastic-wave effect on the motion of oil-bearing bed fluids is of great interest, since goal-directed use of vibroseismic action can enhance oil transfer and extraction. At present, no generally accepted concepts of such a mechanism (or mechanisms) are available. The present article deals with one of the possible mechanisms associated with free-gas liberation due to vibroseismic action.

An oil-bearing bed, as a rule, contains a great amount of dissolved and adsorbed gas. As numerous experiments show, vibration benefits liberation of this gas. This phenomenon is caused by the appearance, in an elastic field, of periodic local rarefactions in a fluid medium, where gas bubble nuclei are formed. Such a bubble in an elastic field makes oscillations relative to its center, which are accompanied by one-sided gas diffusion from the fluid to the bubble, thus causing its rise. The mechanism of such one-sided diffusion is rather simple: under compression gas diffusion from the bubble to the fluid takes place; under extension backward diffusion occurs. Since during extension the diffusion process proceeds through a large surface, the volume of the gas diffusing into the bubble is larger than the volume of the gas liberating from the bubble, thus resulting in the rise of the latter.

The time τ in which the bubble radius is doubled [1] is a characteristic of the one-sided-diffusion process:

$$\tau = (9R_0\rho_g/4\beta_\infty D)(p_0/p_0')^2.$$

This relation yields the important inference that small-size bubbles rise rather rapidly while doubling the radius of large-size bubbles needs more time.

Thus, one-sided diffusion leads us to the conclusion that in an elastic field the initial size distribution of the gas bubbles changes rapidly in the region of small sizes and remains almost stable in the region of large sizes. This gives rise to a shift of the equilibrium values of the gas saturation of a hydrocarbon system, which is equivalent to an increase of its saturation pressure both in a free volume and in porous media (Fig. 1) [2].

Arising gas bubbles clog part of the pore channels, displacing the fluid from them and changing the phase permeabilities of the water and oil containers. Despite the fact that the total permeability of the fluid container may decrease, the permeability of one of the phases may increase. Let, for example, oil saturation be so small that oil is in the unbound state (but near the mobility threshold). In this case, in a hydrophilic medium it occupies the coarsest pores. Because of gas liberation, oil will be displaced into smaller channels, and the mean linear sizes of its pillars will grow. The increased pillars can unite, thus making the oil movable again. Thus, the phase permeability for oil will increase from zero to some positive value. On the three-phase diagram of the phase permeabilities (Fig. 2) this is consistent with the fact that the isolines of the phase permeability for oil that have small values make an angle of more than 60° with the zero gas saturation line. Such a phase diagram is cited, for example, in experimental work [3].

The gas phase becomes bound at further gas liberation. However, if the gas viscosity is much smaller than the viscosities of water and oil, then gas saturation cannot considerably exceed the gas mobility threshold.

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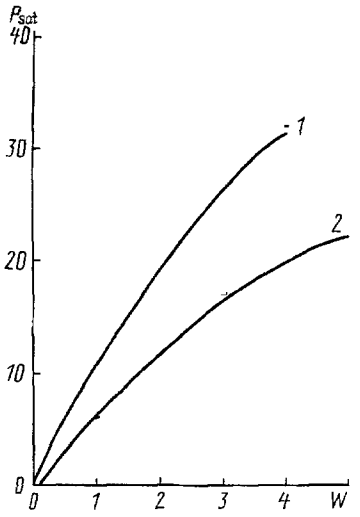

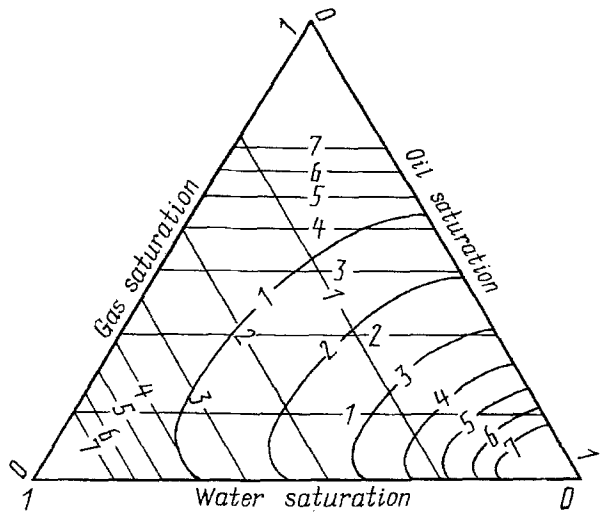

Fig. 1. Variation of the gas saturation pressure (%) of a propane-heptane mixture in an elastic oscillation field: 1) in a porous medium; 2) in a free volume. W, Watts.

Fig. 2. Three-phase diagram of phase permeabilities in the oil-gas-water system. The isolines correspond to the following values of the relative permeability: 1) 0.0; 2) 0.02; 3) 0.1; 4) 0.2; 5) 0.3; 6) 0.4; 7) 0.5.

Let us consider the model of the described process, assuming that the free gas is liberated from oil and the vibration action is equivalent to gas saturation pressure elevation (or gas solubility reduction). Let us use the ordinary three-phase two-component model for an oil-bearing bed fluid [4]. Water saturation, pressure, and mass fraction of the gas component in the total amount of a gas-oil mixture are chosen as the main variables. According to the state equations the remaining variables can be found in terms of these parameters.

Motion of a mixture in a porous medium is described by three mass conservation equations. When the viscosity and density of fluids as functions of the amount of dissolved gas and the system pressure are neglected, the system of fundamental equations assumes the form:

$$m\frac{\partial s_w}{\partial t} = \nabla \frac{k_w}{\mu_w} \nabla p; \tag{1}$$

$$m\frac{\partial}{\partial t}\{\rho_o s_o + \rho_g(1 - s_o - s_w)\} = \nabla\left\{\frac{k_o}{\mu_o}\rho_o + \frac{k_g}{\mu_g}\rho_g\right\}\nabla p; \tag{2}$$

$$m\frac{\partial}{\partial t}\{z\rho_o s_o + \rho_g(1 - s_o - s_w)\} = \nabla\left\{\frac{k_o}{\mu_o}\rho_o r + \frac{k_g}{\mu_g}\rho_g\right\}\Delta p. \tag{3}$$

In addition to the main variables, system (1)-(3) involves oil saturation and the amount of dissolved gas. At equilibrium the relations

$$s_o = \frac{1 - s_w}{1 + \dfrac{\rho_o}{\rho_g(p)}\dfrac{z - r}{1 - z}}; \tag{4}$$

$$r = \min(z,\ R(p)). \tag{5}$$

are valid for them. System (1)-(5) is closed, assuming that the empirical functions of the phase permeabilities and also the gas solubility and density as functions of the pressure R(p) and $\rho_g(p)$ are prescribed. Besides the pressure, these quantities may also depend on other factors. Our model will take account of gas solubility as a function of vibration. In connection with this, relation (5) must be replaced by

$$r = \min(z,\ R(p,\ \nu)). \tag{5'}$$

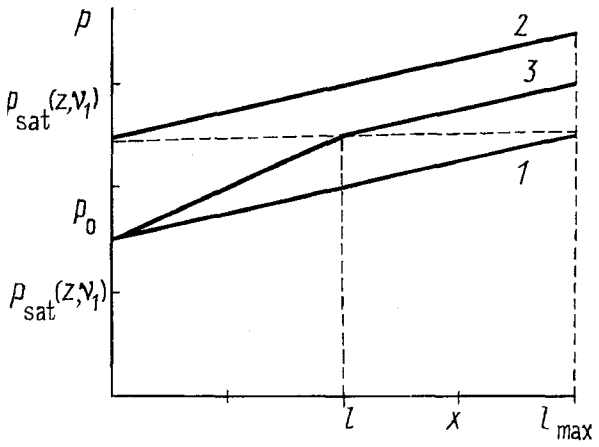

Fig. 3. Pressure distribution evolution between the flooding and extractive galleries under vibroseismic action at constant fluid flowrate (l is the depth of degassing zone advance, l_{max} is the limiting position of the degassing zone): 1) no vibroseismic action; 2) initial stage of vibroseismic action; 3) formation of a quasi-steady degassing zone under vibroseismic action.

As a result of vibration action, we can go from the curve $R(\rho,\nu_0)$ corresponding to the initial state to the curve $R(p, \nu_1)$. Under vibration oil degassing takes place, i.e., the gas solubility at a given pressure decreases: $R(p, \nu_1) < R(p, \nu_0)$ and the saturation pressure increases: $p_{sat}(r,\nu_1) > p_{sat}(r, \nu_0)$.

Note that the problem of choosing the governing parameters and the form of the relation $R(\nu)$ needs special study.

Let us consider the effect of gas liberation on filtration flows in the simplest example of steady water-oil mixture flow between flooding and extractive galleries with a constant flowrate on the flooding and a constant pressure on the extractive galleries. Assume that water saturation and the mass fraction of the gas component in the total amount of the gas-oil mixture are constant along the oil-bearing bed, and the pressure on the extractive gallery exceeds the saturation one. In this case, the pressure will be a linear function of distance from the extractive gallery (straight line 1 in Fig. 3). Let at the initial moment the vibration action start, leading to saturation pressure growth at the extractive gallery above p_0: $p_{sat}(z, \nu_1) > p_0$. Since the fluid in the porous medium is in a closed volume, gas liberation is possible only at the efflux of the corresponding part of the fluid, i.e., a finite time is needed. Therefore, at the first moment no gas liberation occurs but the pressure increases along the entire bed. The pressure near the extractive gallery rises so much that no degassing starts, i.e., up to the quantity $p'_0 = p_{sat}(z, \nu_1)$. Mathematically, this is consistent with the fact that under the boundary condition $p'_0 < p_{sat}(z, \nu_1)$, problem (1)-(5′) has no solutions. On physical grounds, the pressure rises due to liberation of an "infinitesimal" amount of the gas in the form of bubbles. Thus, at the first moment, the saturations and hence the phase permeabilities have not had time to change, so that the pressure distribution remains linear and takes the form of curve 2 (Fig. 3).

At the extractive gallery boundary a pressure drop $p'_0 - p_0$ arises. It generates an elevated fluid efflux velocity into the gallery, which exceeds the flooding one. In what follows, the freed pore space is occupied by the liberated gas (similarly to the dissolved-gas regime). A wave of degassing and pressure reduction below $p_{sat}(z, \nu_1)$ will move from the extractive to the flooding gallery with a decreasing velocity. The pressure gradient in the degassing zone will decrease, remaining greater than the mean bed pressure gradient. The degassing wave front is determined by the condition $p = p_{sat}(z, \nu_1)$.

Since the depth of degassing wave advance is limited beforehand (by the quantity l_{max} in Fig. 3), its limiting position and the corresponding limiting pressure distribution exist. Generally speaking, this is an "intermediate" limit because, as will be shown below, the limiting state for the degassing process will still not be steady with respect to water and oil saturations. The limiting pressure distribution after formation of the quasi-steady degassing zone is shown by line 3 in Fig. 3. At the point $x=l$ the pressure equals the saturation one $p_{sat}(z, \nu_1)$ and has a gas saturation

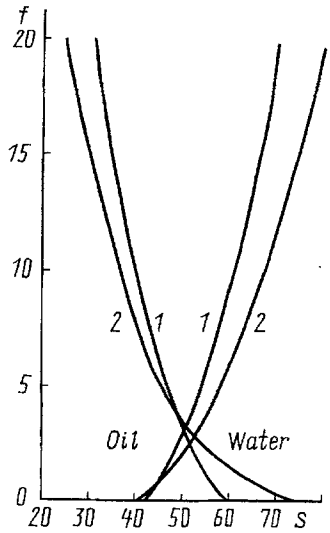

Fig. 4. Variation of relative phase permeabilities f for water and oil at gas liberation due to vibroseismic action: 1) no action; 2) in an elastic-oscillation field. f, s, %.

jump: $s_g = 0$ at $x = l$ and $s_g \geq s_g^0$ at $x \leq l$. The zone with an intermediate saturation $0 < s_g < s_g^0$ exists in dynamics but disappears in the limit.

If the gas viscosity may be considered small ($\mu_g \ll \mu_w, \mu_o$), then the entire gas liberating above the threshold saturation s_g practically does not remain in the bed; therefore, without a great error it may be considered that the gas saturation in the entire degassing zone is constant and equal to s_g^0. The characteristic time of degassing zone formation may be estimated as

$$t \simeq \frac{l s_g^0 m \rho_g(p_0)}{q k_o(s_w, s_o) \rho_o (z - R(p_0))} .$$

Note that degassing of oil in the oil-bearing bed must result in some decrease of the amount of gas produced on the extractive gallery.

When the degassing zone is formed, a greater amount of fluid flows through the boundary x = 0 than that which enters through the boundary $x = l$. Fluids efflux according to their mobilities; therefore, their mean saturations (in the degassing zone) change differently. Let us consider two limiting cases.

1. Oil saturation s_o is close to the mobility threshold s_o^0, i.e., $s_o - s_o^0 \leq 1$. In this situation, water is the main fraction of the outflowing fluid. As a result, water saturation in the degassing zone is reduced, i.e., the gas as if displaces water (here separate pore channels are not the issue). The oil saturation practically does not change. Thus, the phase permeability for water is reduced and the one for oil remains invariable, i.e., product flooding decreases.

2. Water saturation s_w is close to the mobility threshold (i.e., $s_w - s_w^0 \ll 1$). In this case, in the degassing zone oil mainly escapes, and oil saturation decreases, thus raising the flooding.

Fluid efflux to the extractive well may be considerated similarly. Here, the degassing zone expanding from the well is also formed, characterized by elevated pressure gradients. The conclusion holds true that the well product flooding decreases if it was high and increases if it was low before vibration action. Note that such behavior of well flooding due to pre- and aftershock vibrations under an earthquake was observed in practice many times [5].

Generally speaking, appearance of the gas phase increases the filtration resistance of a bed, i.e., at a constant pressure drop the well fluid flow decreases. However, against this background at large product flooding the oil flow may grow owing to the above specific features of the phase permeability diagram.

Indeed, in response to the above-described fast dynamic processes of gas liberation the bed proves to be composed of two regions: far from the extractive well no free gas will occur, and in the degassing zone the gas saturation will be close to s_g^0. From the viewpoint of water and oil motion, the filling of part of the pore space with the

TABLE 1. Product Flooding Change due to Vibroaction

Initial water saturation	Initial flooding, %	Flooding after forming a degassing zone, %
0.30	0.4	0.8
0.35	2.5	3.5
0.40	9.3	10.9
0.65	98.3	94.3

gas is equivalent to a porosity decrease $\tilde{m} = m(1-s_g^0)$ and a saturation change $\tilde{s}_w = s_w/(1-s_g^0)$, $\tilde{s}_o = s_o/(1-s_g^0)$. Relative phase permeabilities for water and for oil as functions of recalculated water saturation assume the form

$$\tilde{f}_w(\tilde{s}_w) = k_w(s_w, s_o)/k = k_w(\tilde{s}_w(1-s_g^0), (1-s_g^0)(1-\tilde{s}_w))/k,$$
$$\tilde{f}_o(\tilde{s}_w) = k_o(s_w, s_o)/k = k_o(\tilde{s}_w(1-s_g^0), (1-\tilde{s}_w)(1-s_g^0))/k. \quad (6)$$

In Fig. 4 are shown relative phase permeabilities with no free gas (no action) and under vibroseismic action in the degassing zone at a gas saturation s_g^0 (all curves correspond to the three-phase diagram in Fig. 2). From Fig. 4 it is seen that if the water mobility always decreases under the vibroaction due to free-gas liberation in a bed, then the oil mobility may decrease as well as increase, depending on the saturation. Increase of the oil mobility takes place at high flooding. In this case, the point of vanishing of the phase permeability for oil is shifted to the right, i.e., not only oil efflux enhancement (at a constant pressure drop) but also final oil transfer increase occurs.

The above qualitative results were checked by numerical modeling by the linear two-dimensional filtration model, allowing for fluid compressibility and the volume coefficient of oil, in the example of the Teterevo-Mortem'yanovsk oil bed. Numerical results are cited in Table 1. As is seen, low floodings of a filtrating fluid after vibroaction at the bed exit increase and high ones decrease.

The presented results show that it is expedient to use vibroseismic action at the final stage of oil deposit exploitation with high product flooding.

NOTATION

m, porosity; k, absolute permeability; k_w, k_o, k_g, phase permeabilities of water, oil, gas, respectively; ρ, density; μ, viscosity; s, saturation; p, pressure; p_0, hydrostatic pressure; p'_0, pressure oscillation amplitude; x, distance; p_{sat}, saturation pressure; z, mass fraction of the dissolved gas in oil; R(p), gas solubility in oil (maximum amount of gas dissolved in 1 kg of oil at a given pressure); ν, set of a governing vibration parameters; q, fluid flowrate; t, time; R_0, initial radius of a gas bubble; D, diffusion coefficient; β_0, gas concentration in the fluid far from a bubble; W, vibrosource power. Indices w, o, g refer to the water, oil, gas parameters, respectively.

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