GRAVITY SEGREGATION IN A HOMOGENEOUS WATERFLOODED STRATUM IN A SEISMOACOUSTIC FIELD

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The oil saturation distribution in a homogeneous waterflooded oil stratum in a seismoacoustic field is calculated in a computer experiment based on a theoretical model of capillary–gravity segregation.

The recovery of residual petroleum in waterflooded strata after the completion of drilling operations is an important problem in the national economy. Petroleum-industrial practice indicates that natural capillary–gravity segregation of water and oil takes place in the stratum after the completion of drilling operations and the shutdown of production and injection wells.

The absolute and relative permeability of the immiscible phases, the viscosity of the oil, the surface tension at the phase interfaces, and the capillary pressure all change in flooded oil strata with a seismoacoustic environment [1]. We have therefore undertaken a numerical assessment of the influence of these parameters on the distribution of the oil saturation in homogeneous horizontal strata.

The theoretical model of the dynamics of uniform segregation of immiscible fluids in a horizontal stratification is summarized as follows [2].

Let a horizontal stratification consist of d interlayers (seams) with absolute permeabilities k_j ($j = 1, \ldots, d$). The equation for the segregation process in a stratification can be obtained from the system of equations describing the uniform two-phase filtration of immiscible incompressible fluids in a homogeneous-permeability porous medium:

$$v_1 = -\frac{k(x)\,k_1(s)}{\mu_1}\left(\frac{\partial p_1}{\partial x} + \gamma_1\right); \quad v_2 = -\frac{k(x)\,k_2(s)}{\mu_2}\left(\frac{\partial p_2}{\partial x} + \gamma_2\right);$$
$$\frac{\partial v_1}{\partial x} = -m\frac{\partial s}{\partial t}; \quad \frac{\partial v_2}{\partial x} = m\frac{\partial s}{\partial t}; \quad p_c = p_1 - p_2. \tag{1}$$

Let the coordinate origin be located at the base of the stratum and be directed vertically upward, and let x_j be the coordinate of the common boundary of the j-th and (j + 1)-st seams. Assuming that the total filtration rate $v = v_1 + v_2$ is equal to zero, we can reduce the system (1) to the equation

$$\frac{\partial}{\partial x}\left\{\frac{k_j k(s)}{\mu_1}\left(\frac{\partial p_c^j}{\partial x} - \Delta\gamma\right)\left[1 + \mu_0\,\frac{k_1(s)}{k_2(s)}\right]^{-1}\right\} = m\frac{\partial s}{\partial t}, \quad \Delta\gamma = \gamma_2 - \gamma_1;\ \mu_0 = \mu_2/\mu_1. \tag{2}$$

Here $k_j = k(x)$ at $x_{j-1} \le x \le x_j$, $x_0 = 0$, and $x_d = H$.

Interface conditions must be satisfied at points of discontinuity of the coefficients of the function k(x); these conditions are deduced from the requirement of continuity of the flows and capillary pressure:

$$v_i(x_j - 0,\ t) = v_i(x_j + 0,\ t), \tag{3}$$
$$p_c^j(x_j - 0,\ t) = p_c^j(x_j + 0,\ t). \tag{4}$$

It follows from condition (4) that the saturation distribution is discontinuous at points of discontinuity of the coefficients. This creates difficulties in the numerical integration

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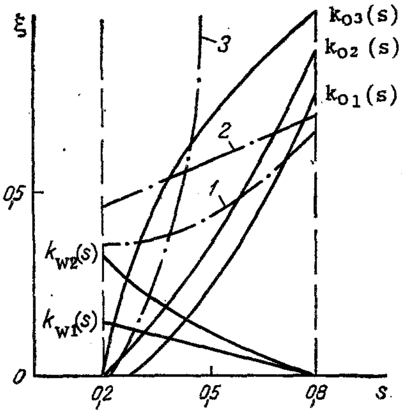

Fig. 1

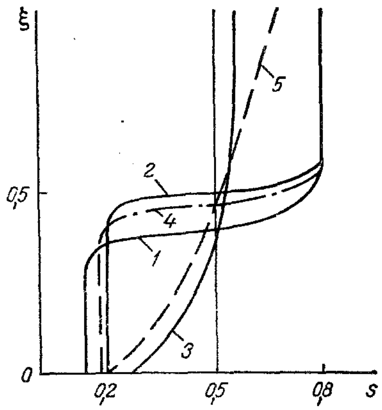

Fig. 2

Fig. 1. Leverett functions and relative permeability curves used in the computer experiment. 1) $f(s) = 0.9\ (s - 0.2)^2 + 0.35$; 2) $f(s) = 0.4s + 0.4$; 3) $f(s) = 0.05669\ (0.7 - s)^{-2} - 0.242$.

Fig. 2. Statistical distribution of oil saturation as a function of the capillary pressures and absolute permeabilities. 1) $t(s) = 0.9\ (s - 0.2)^2 + 0.35$; 2) $f(s) = 0.4s + 0.4$; 3) $f(s) = 0.05669\ (0.7 - s)^{-2} - 0.242$; 4) $k = 1\ \mu m^2$; 5) $k = 0.01\ \mu m^2$.

TABLE 1. Input Data for the Computer Experiment

Parameters of stratum and saturating phases	Expt. No.		
	1	2	3
No. of seams	1	1	1
Abs. permeability, μm^2	varies	1	1
Initial oil saturation distribution	0,5	0,5	0,5
Interphase tension, J/m^2	0,02	0,02	0,02
Oil viscosity, mPa·sec	2,0	varies	2,0
Water viscosity, mPa·sec	1,0	1,0	1,0
Difference in densities of oil and water, kg/m^3	340	340	340
Stratum thickness, m	15	15	15
Porosity	0,25	0,25	0,25

of Eq. (2), because standard homogeneous shock-capturing differencing schemes do not work for equations with discontinuous coefficients.

In order to synthesize a homogeneous shock-capturing differencing scheme, we "smear" the permeability discontinuities, replacing the piecewise-constant permeability by a continuous function:

$$k^*(\xi) = \begin{cases} k_{j-1}/k_0 & \text{for } \xi_{i-1} + \varepsilon \leqslant \xi \leqslant \xi_j - \varepsilon, \\ [(k_j - k_{j-1})(\xi - \xi_j) + (k_j + k_{j+1})\varepsilon](2k_0\varepsilon)^{-1} & \text{for } \xi_{j-1} - \varepsilon \leqslant \xi \leqslant \xi_j + \varepsilon, \\ k_j/k_0 & \text{for } \xi_j + \varepsilon \leqslant \xi \leqslant \xi_{i-1}\varepsilon. \end{cases}$$

Reducing Eq. (2) to dimensionless form, we approximate it by a differencing scheme whose solution is reducible to the solution of our boundary-value problem.

The given algorithm was checked out on a BÉSM-6 computer and was used to investigate the influence of the above-indicated parameters on the oil saturation of a flooded stratum.

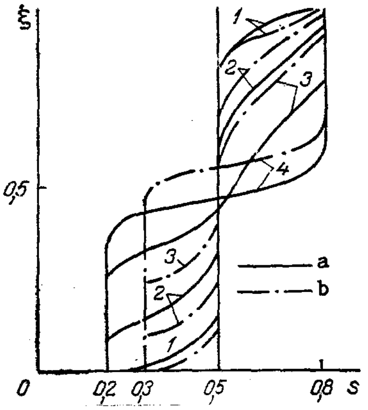

Fig. 3. Dynamics of capillary-gravity segregation in dependence on the relative permeabilities for oil and water: a) $k_{oil}(s) = k_{o1}(s)$; $k_{water}(s) = k_{w1}(s)$; b) $k_{oil}(s) = k_{o2}(s)$; $k_{water}(s) = k_{w2}(s)$; 1) 0.1 month; 2) 0.5 months; 3) 1 month; 4) 3 months.

TABLE 2. Height Distribution of Oil Saturation in Stratum as a Function of Relative Permeability for Oil

Rel. height in stratum	$k_{o1}(s)$	$k_{o2}(s)$	$k_{o3}(s)$	Rel. height in stratum	$k_{o1}(s)$	$k_{o2}(s)$	$k_{o3}(s)$
0	0	0	0	0,50	0,30	0,65	0,80
0,10	0,30	0,20	0,20	0,55	0,48	0,75	0,80
0,30	0,30	0,20	0,20	0,60	0,66	0,80	0,80
0,40	0,30	0,20	0,55	0,80	0,80	0,80	0,80
0,45	0,30	0,40	0,73	1,00	0,80	0,80	0,80

1. ABSOLUTE PERMEABILITY

According to prevailing notions, the absolute permeability of a stratum can increase by two orders of magnitude in a seismoacoustic field [3]. We therefore set up the following computer experiment. We specify the parameters of the stratum and of the immiscible phases, which are summarized in Table 1 (experiment No. 1).

We specify the dependence of the relative permeabilities and the Leverett function on the oil saturation in the form of the curves shown in Fig. 1: $k_{oil}(s) = k_{o2}(s)$, $k_{water}(s) = k_{w1}(s)$, $f(s) = 0.9\,(s - 0.2)^2 + 0.35$.

Some of the results characterizing the variations of the oil saturation along the thickness of the stratum in static equilibrium are shown in Fig. 2. Curve 5 characterizes the steady-state variation of the oil saturation along the thickness of a stratum with a permeability of 0.01 μm² at 100 months after the beginning of segregation, and curve 4 shows the steady-state variation of the oil saturation along the thickness of the stratum after seismic activity, which increased the absolute permeability by two orders of magnitude (to 1 μm²) three months after the beginning of the activity. It is evident from a comparison of these curves that segregation can proceed very efficiently during such activity. For example, in the lower half of the stratum cross section ($\xi = 0.2$) the water saturation is equal to 0.62 after 100 months under the conditions of natural gravity separation and is equal to 0.82 after three months during seismic activity. Similarly, in the upper part of the stratum cross section ($\xi = 0.7$) the soil saturation is equal to 0.58 after 100 months under the conditions of natural gravity separation and is equal to 0.80 after three months during seismic activity. The system attains static equilibrium as a result of seismoacoustic activity 33 times faster than in the presence of natural separation (100 vs 3 months). Consequently, the increase in the absolute permeability of the stratum during seismoacoustic activity should increase and accelerate petroleum recovery.

2. OIL VISCOSITY

Seismoacoustic activity induces a severalfold reduction in the oil viscosity. The parameters given in Table 1 for experiment No. 2 are specified accordingly. Calculations show that the qualitative aspect of the segregation process remains more or less the same, i.e., the oil saturation curves $s(\xi, t)$ in static equilibrium up to the time of redistribution of the phases coincide, regardless of the specified viscosity of the oil. However, the quantitative differences are very appreciable in real time scale. For example, static equilibrium for segregation is attained after 3, 10, and 50 months for oil viscosities of 5, 50, and 100 mPa·sec, respectively.

Consequently, the reduction of the oil viscosity during seismoacoustic activity does not influence the steady-state distribution of the oil saturation, but it accelerates the redistribution of the phases considerably.

3. CAPILLARY PRESSURE

Here we fix the initial data for the calculations (Table 1, experiment No. 3) and specify the variation of the relative phase permeabilities as a function of the oil saturation in the form $k_{oil}(s) = k_{o3}(s)$, $k_{water}(s) = k_{w1}(s)$ (Fig. 1). Since the interphase tension, absolute permeability, and porosity of the stratum are fixed, the variation of the Leverett function actually implies a variation of the capillary pressure.

The Leverett functions are chosen in the form $f(s) = 0.4s + 0.4$ (curve 1 in Fig. 1) and $f(s) = 0.9(s - 0.2)^2 + 0.35$ (curve 2).

The steady-state distributions of the oil saturation in the stratum are shown in Fig. 2 (curves 1 and 2). It is evident from the figure that a reduction in the capillary pressure enhances the segregation process. Indeed, at a relative height in the stratum of, e.g., $\xi = 0.5$ the oil saturation corresponding to the higher capillary pressure (curve 1) is equal to 0.79. It follows from theoretical considerations that the seismoacoustic field lowers the capillary pressure, and so it can be concluded that seismoacoustic activity affects the stratum in this case by increasing the oil saturation in the upper part of the stratum and increasing the water saturation in the lower part.

4. RELATIVE PHASE PERMEABILITIES OF WATER AND OIL

The initial data for the calculations are given in Table 1, experiment No. 3. We specify the Leverett function in the form $f(s) = 0.9(s - 0.2)^2 + 0.35$.

We specify the variation of the relative phase permeabilities for water and oil as a function of the oil saturation by the functions shown in Fig. 1: $k_{water}(s) = k_{w1}(s)$, $k_{oil}(s) = k_{o1}(s)$, $k_{o2}(s)$, $k_{o3}(s)$.

The results of the calculations for the steady-state oil saturation distribution, which is established after three months, are given in Table 2. It is evident from the table that higher values of the relative permeabilities for oil correspond to higher values of the oil saturation in the upper part of the stratum.

The relative permeability increases for both the water and the oil under conditions of seismoacoustic activity. We therefore varied the relative permeabilities for the water and the oil in the next computer experiment (see Fig. 1). We fix the Leverett function: $f(s) = 0.9 \times (s - 0.2)^2 + 0.35$ and assign all other parameters as in Table 1, experiment No. 3. Figure 3 shows the dynamics of capillary-gravity segregation for $k_{water}(s) = k_{w1}(s)$, $k_{oil}(s) = k_{o1}(s)$ (solid curve) and for $k_{water}(s) = k_{w2}(s)$, $k_{oil}(s) = k_{o2}(s)$ (dot-dash curve). The distribution of the immiscible phases attains the steady state after three months in both cases. An analysis of the curves shows that the increase in the relative permeabilities for oil and water in the lower part of the stratum causes the water saturation to increase there and, accordingly, the oil saturation to decrease.

For example, at a relative height $\xi = 0.2$ the value of the oil saturation corresponding to the lower relative permeability curve after 0.5 month is equal to 0.47, and the value corresponding to the upper curve is equal to 0.41. The increase in the relative permeabilities in the upper part of the stratum, on the other hand, causes the oil saturation to increase (e.g., the oil saturation after one month at $\xi = 0.7$ is equal to 0.56 for lower relative permeabilities and is equal to 0.68 for higher permeabilities). Thus, the increase in the relative permeabilities for oil and water establishes conditions for a more rapid redistribution of the phases, the water tending downward and the oil migrating upward.

NOTATION

x, length coordinate; t, time; k(x), absolute permeability of porous medium; s, saturation of nonwetting phase, v_i, filtration rate of i-th phase; μ_i, viscosity of i-th phase; $k_i(s)$, relative phase permeability; γ_i, bulk density; p_i, pressure in the phase; p_c, capillary pressure; i = 1, nonwetting phase; i = 2, wetting phase, x_j, coordinate of common boundary of j-th and (j + 1)-st seams; H, stratum thickness; p_c^j, capillary pressure in j-th seam; ε, a sufficiently small number; k_0, characteristic permeability; σ, interphase tension; f(s), Leverett function; $\xi = x/H$, relative height in stratum.

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