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Abstract

Full Text

HYDROMECHANICS

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DISPLACEMENT OF A TWO-COMPONENT MIXTURE WHEN ONE OF THE DISPLACED LIQUIDS HAS LOW VISCOSITY

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In hydrodynamic calculations of the development of oil fields, in some cases one can use the results of solving the problem of the filtration of a three-component system of incompressible mutually immiscible liquids. We shall consider here the flow that arises when a two-component mixture of liquids 1 and 2, initially contained in a porous medium, is displaced by liquid 3. In doing so, bearing in mind the displacement of a gas-oil mixture at constant reservoir pressure, we shall assume that the viscosity of the displaced liquid 1 is much less than the viscosities of the other two.

The penetration of liquid 3 into a medium initially occupied by the mixture leads to the formation of a region of three-component flow in the interval from the initial position of the displacing liquid to the boundary of its greatest advance.

The filtration velocities of the components may be represented in the form

$$\mathbf{U}_i^{\exists} = f_i \mathbf{U},$$

where $U = U_1 + U_2 + U_3$ and f_i is the relative content of the i -th component. Owing to the incompressibility of the liquids,

$$(\nabla \mathbf{U}) = 0.$$

The continuity equations for a multicomponent mixture ^(3,4) may be written in the form

$$(\mathbf{U} \nabla f_i) = -m \frac{\partial \rho_i}{\partial t}, \quad (1)$$

where m is the porosity and ρ_i is the saturation by the i -th component. Since $\rho_1 + \rho_2 + \rho_3 = 1$, the number of equations in system (1) is two.

Let us consider flow in an elementary stream tube whose shape does not change with time ⁽⁵⁾, under initial conditions of the form

$$\rho_3|_{t=0} = \text{const} \leq \rho_{3 \text{ residual}}, \quad \rho_2|_{t=0} = \rho_{20}(S).$$

In the two-component region, from (1) we obtain

$$U(S)\Phi_2(\rho_2)\frac{\partial\rho_2}{\partial S} + m\frac{\partial\rho_2}{\partial t} = 0, \quad (2)$$

where S is the path length and $\Phi_2(\rho_2) = df_2/d\rho_2$.

The function $f_2(\rho_2)$ is expressed through the ratio $F_1(\rho_2)/F_2(\rho_2) = \Psi_{12}(\rho_2)$:

$$f_2 = \frac{1}{1 + \Psi_{12}\mu_{21}^*}, \quad (3)$$

where $\mu_{21}^* = \mu_2/\mu_1$.

The solution of equation (2) has the form

$$\nu[S(\rho_2)] - \nu[S_0(\rho_2)] = \frac{\Phi_2(\rho_2)}{m} \delta(t), \quad (4)$$

where $\nu(S) - \nu(S_0)$ is the volume of the stream tube in the segment from S_0 to S , and $\delta(t)$ is the volume of fluid that has passed through the sections of the stream tube (5). It follows from (4) that the volumetric relations are the same for all one-dimensional flows.

Assume that at $t = 0$, $\rho_{20} = \text{const}$. In this case both fluids are mobile, i.e. $\rho_{2 \text{ res}} < \rho_{20} < \rho_{2 \text{ max}}$. In addition, before displacement begins, the porous medium contains an immobile fluid 3 with saturation $\rho_{30} \leq \rho_{3 \text{ res}}$.

The change in saturation in the region of two-component flow is shown in Fig. 2 in the domain

$$xm / \int_0^t U dt \geq \Phi_{\phi 32}.$$

The saturation at the front is determined from the material-balance equation

$$(\rho_{2\phi} - \rho_{20})\Phi_2(\rho_{2\phi}) = f_2(\rho_{2\phi}) - f_2(\rho_{20}). \quad (5)$$

In the problem under consideration it is assumed that $\mu_{21}^* \gg 1$. Calculations show (Fig. 2) that, determining $\rho_{2\phi}$ in this case from (5), we obtain

$$\rho_{2\phi} \cong \rho_{2 \max},$$

i.e. the low-viscosity fluid is displaced in such a way that its content behind the displacement front is close to the minimum residual content.

In this case, from (5) we obtain

$$\Phi_2(\rho_{2\phi}) \cong \frac{1 - f_2(\rho_{20})}{\rho_{2 \max} - \rho_{20}} = \frac{1 - \frac{1}{1 + \Psi_{12}\mu_{21}^*}}{\Delta\rho_2}. \quad (6)$$

The displacement front between fluids 1 and 2 moves with velocity

$$W_{\phi 21} = \frac{U}{m} \Phi_{2\phi} = \frac{U \left[1 - \frac{1}{1 + \Psi_{12}\mu_{21}^*} \right]}{m\Delta\rho_2}. \quad (7)$$

Fig. 1. Phase permeability for the wetting phase F_c ; permeability ratio $F_c/F_{nc} = \Psi$; distribution function Φ as a function of the saturation of the wetting phase ρ . Uncemented sand, parameter

$$\frac{\sigma L}{K_0 \partial P / \partial x} = 1.3 \cdot 10^6.$$

For calculations it is necessary, strictly speaking, to have the dependences $f_2(\rho_2)$ and $\Phi_2(\rho_2)$, determined for two-component flow in the presence of a bound third component. The results of work (10) show that these functions are sufficiently close to the dependences for two-component flow presented in Fig. 1. The presence of a bound third component, as experiments show, is in a number of cases approximately equivalent to a corresponding increase in the volume of the solid skeleton. To take ρ_{30} into account in the equations

in (5), (6), and (7) the fictitious saturation $\rho_2^* = \frac{\rho_2}{1 - \rho_{30}}$ and the fictitious porosity $m^* = m(1 - \rho_{30})$ are introduced.

Let us now consider the region of three-component flow. According to the preceding discussion, behind the displacement front, for $xm / \int_0^t U dt < \Phi_{\phi 21}$, the saturation $\rho_1 \simeq \rho_{1ost} = \text{const}$ and $\partial\rho_1/\partial S \simeq 0$. From system (1) we obtain

$$U(S)\Phi_3(\rho_3, \rho_1) \frac{\partial\rho_3}{\partial S} + m \frac{\partial\rho_3}{\partial t} = 0, \quad (2')$$

where $\Phi_3(\rho_3, \rho_1) = df_3(\rho_3, \rho_1)/d\rho_3$.

The distribution of the saturation ρ_3 , when the displacing component 3 penetrates into a region containing the almost immobile component 1 and the mobile component 2, is determined from equation (2'), which has the same form as (2) in the region of two-component flow. For the calculations the functions f and Φ of the two-component mixture may be used (Fig. 1). The effect of the residual saturation ρ_{1ost} is likewise taken into account by reducing the porosity.

Fig. 2. Distribution of saturations along the displacement length. For the calculations, the data of Fig. 1 were used. Component 2 is assumed to be wetting in the liquid system 1–2, and component 3 wetting in the system 2–3.

The distribution $\rho \left(xm / \int_0^t U dt \right)$ has the form usual for two-component flow. At the boundary between liquids 2 and 3 a saturation discontinuity is formed, moving with velocity

$$W_{\phi 32} = \frac{U}{m(1 - \rho_{1ost})} \Phi_3(\rho_{3\phi}^*). \quad (8)$$

Here we restrict ourselves to considering flow in which the value $\Phi_{\phi 32}$, determined by known methods from the material-balance relation ^(1,7,8), is less than $\Phi_{\phi 21}$, and consequently $W_{\phi 32} < W_{\phi 21}$.

The distribution of saturations along the displacement length for the entire flow is shown in Fig. 2. It follows from the preceding discussion that two regions are formed, $xm / \int_0^t U dt < \Phi_{\phi 32}$ and $xm / \int_0^t U dt > \Phi_{\phi 32}$, in each of which two-component motion is realized approximately or exactly. The region in which two-component motion is realized exactly, in turn, breaks up into a region of approximately single-component flow for

$$\Phi_{\phi 32} < \frac{mx}{\int_0^t U dt} < \Phi_{\phi 21}$$

and a region of undisturbed two-component flow for

$$\frac{mx}{\int_0^t U dt} > \Phi_{\phi 21}.$$

In general, the three-component flow under consideration can, with sufficient approximation, be represented as two two-component flows separated by a region of single-component flow. A characteristic feature of the displacement process in this case is that the single-component region increases and the mobile part of

Fig. 3

Figure 1: Fig. 3

the low-viscosity component is almost completely extracted, after which liquid 2 is displaced by liquid 3.

Flow of this kind was realized in experiments on the displacement of oil by water in the presence of free gas ⁽⁹⁾. In ⁽⁹⁾ it is also indicated that the results obtained can be explained if it is assumed that the distribu-

the saturation distribution has the form, close to the dependence $\rho = \rho \left(xm / \int_0^t U dt \right)$, following from the theoretical consideration (Fig. 2). The immobility of liquid 2 until the moment of completion of displacement of liquid 1, noted in work ⁽⁹⁾, does not agree with the results of the theory and is not observed in experiments carried out on large models under conditions approximately similar to natural ones, i.e., for a small value of the ratio of capillary pressure to the total pressure drop and when self-similarity with respect to the parameter

$$\frac{\sigma L}{K_0 \partial P / \partial x}$$

is attained. Measurements show that in such experiments the content of liquid 2 in the total flow rate in the first period can in a number of cases be very small, in accordance with expression (3), but always remains different from zero. In Fig. 3 the initial part of the dependence $\bar{V}_2(\bar{V}_{inj})$ is additionally given on an enlarged scale.

Fig. 3. Displacement of a mixture of nitrogen and kerosene by water. Relative produced volumes as functions of the relative injected volume. $\mu_w = 1.0$; $\mu_{ker} = 1.8$ cP; $\mu_{gas} = 0.0018$ cP; $\rho_{w,thr} = 0.163$; $\rho_{ker} = 0.435$; $\rho_{r,res} = 0.176$. *a*—experimental data, *b*—calculation.

Establishing the character of the process and the form of the dependence $\rho \left(xm / \int_0^t U dt \right)$ makes it possible, using the known relations of the theory of two-liquid flows ^(6, 2) and formulas (6), (7), (8), to obtain expressions for calculating displacement characteristics. Satisfactory agreement with experiment* (Fig. 3) was obtained by using the dependences $f(\rho)$ and $\Phi(\rho)$ of two-component flow, while the influence of the third bound component was approximately taken into account by means of a decrease in porosity.

It can be shown that, at a distance from wells, the filtration equations for gasified oil ⁽¹¹⁾, with constancy of reservoir pressure, pass into equations of the form (2). This permits the results obtained in the present work to be applied to calculating

oil and gas production during water flooding begun after development under the solution-gas-drive regime. Calculations show that in this case, for low-viscosity oils, some increase in oil recovery is usually achieved.

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* The experiments were conducted by S. A. Kundin.

Note: Figure translations are in progress. See original paper for figures.

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