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CAPILLARY PERMEATION OF HYDROPHOBIC OIL-SATURATED ROCKS BY A SOLUTION OF AN ACTIVE ADMIXTURE

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It is well known (see, e.g., [1-3]) that capillary permeation plays an important role in extracting oil from heterogeneous (layered-nonuniform, fractured-porous, and so on) strata. As a result of capillary permeation, water penetrates to the less permeable parts of the stratum, in which oil turns out not to have been displaced by frontal flooding. This mechanism assumes that water has better wetting ability than oil (i.e. the rocks are hydrophilic), and for this reason, under conditions of capillary balance, water predominately fills regions with small pores. In a number of cases, the rocks turn out to be hydrophobic as a result of adsorbing active components in oil on their surfaces and the process of capillary permeation cannot proceed, which decreases the oil recovery from the stratum.

One of the means for increasing oil recovery in such cases is adding surfactants to the water that is pumped in [4, 5], which, being adsorbed on the surface of the porous framework, make the surface hydrophilic. Since the process of making the surface hydrophilic must precede permeation, the surfactant must be soluble to some extent (even a small extent) in oil.

In the present work, we examine the simplest description of such a permeation process for an initially hydrophobic rock by a water solution of an active admixture that makes the rock hydrophilic. This case differs from the previously examined [6] problem of counterflow capillary permeation of a porous medium by a solution of an active admixture by the fact that it is necessary to take into account the solubility of the active admixture in oil and the change in the sign of the capillary pressure (the medium becomes hydrophilic); as will be evident from the results, the permeation rate in the case being examined depends in a characteristic way on the rate of the diffusion of the active admixture.

1. We will write the equations for two-phase flow in a porous medium in the presence of an active admixture, assuming that local conditions for thermodynamic equilibrium between the admixture dissolved in water and in oil and that adsorbed by the porous medium are satisfied:

$$ms_{,t} + \operatorname{div} \mathbf{u}_1 = 0,\ \operatorname{div}(\mathbf{u}_1 + \mathbf{u}_2) = 0; \tag{1.1}$$

$$[mc_1 s + m(1-s)c_2 + a]_{,t} + \operatorname{div}(c_1\mathbf{u}_1 + c_2\mathbf{u}_2) + \operatorname{div}\mathbf{q} = 0; \tag{1.2}$$

$$c_1 = c,\ c_2 = \varphi(c),\ a = a(c, s),\ \mathbf{q} = -D\nabla c,\ D = D(c, s); \tag{1.3}$$

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$$\mathbf{u}_1 = -\frac{k}{\mu_i} f_i(s, c) \nabla p_i \quad (i = 1, 2); \tag{1.4}$$

$$p_2 - p_1 = P_c(s, c). \tag{1.5}$$

where s is the water saturation; m is the porosity; k is the permeability of the porous medium; u_i are the phase percolation rates; c_i are the admixture concentrations in the phases; a is the amount of admixture adsorbed; q is the diffusion transport of the admixture; D is the diffusion coefficient; p_i are the phase pressures; f_i are the phase permeabilities; μ_i are the phase viscosities; P_c is the capillary pressure; the index 1 refers to water and the index 2 refers to oil. The equations presented above differ from the corresponding equations in [6] only by the fact that the solubility of the admixture in oil ($c_2 \neq 0$), characterized by an equilibrium function ($c_2 = \varphi(c)$), is taken into account.

The problem of counterflow capillary permeation corresponds to one-dimensional rectilinear-parallel motion with the total percolation rate equal to zero:

$$s = s(x, t),\ c = c(x, t),\ \mathbf{u}_i = (u_i, 0, 0),\ u_1 = -u_2 = U(x, t).$$

At the same time, from Eqs. (1.1)-(1.5), it follows that

$$m\frac{\partial s}{\partial t} + \frac{\partial u}{\partial x} = 0,$$

$$[ms + m(1 - s)\varphi'(c)]\frac{\partial c}{\partial t} + \frac{\partial a(c, s)}{\partial t} + u[1 - \varphi'(c)]\frac{\partial c}{\partial x} = \frac{\partial}{\partial x}\left(D\frac{\partial c}{\partial x}\right),$$

$$u = \frac{k}{\mu_1}\frac{f_1 f_2}{\mu f_1 + f_2}\frac{\partial P_c}{\partial x}, \quad P_c = P_c(s, c), \quad \mu = \mu_2/\mu_1.$$

With natural initial and boundary conditions,

$$s(x, 0) = s_0,\ c(x, 0) = c_0,\ s(0, t) = s^0,\ c(0, t) = c^0$$

the problem has a self-similar solution of the form

$$s = S(\xi), \quad c = C(\xi), \quad \xi = x/a_* \sqrt{t}, \quad a_*^2 = k\Pi/\mu,$$

where the functions S and C are solutions of the problem

$$\frac{d}{d\xi}\left[\alpha\frac{dP_c}{d\xi}\right] + \frac{\xi}{2}\frac{ds}{d\xi} = 0, \quad \alpha = -\frac{f_1 f_2}{m(\mu f_1 + f_2)}; \tag{1.6}$$

$$\frac{d}{d\xi}\left(\frac{D}{a_*^2 m}\frac{dc}{d\xi}\right) + \left[\frac{\xi}{2}(s + (1 - s)\varphi'(c))\frac{dc}{d\xi} + \frac{\xi}{2}\frac{da}{d\xi} + \right.$$
$$\left. + (1 - \varphi'(c))\alpha\frac{dP_c}{d\xi}\right]\frac{dc}{d\xi} = 0, \frac{dP_c}{d\xi} = \frac{\partial P_c}{\partial c}\frac{dc}{d\xi} + \frac{\partial P_c}{\partial s}\frac{ds}{d\xi}, \tag{1.7}$$
$$s(0) = s^0,\ s(\infty) = s_0,\ c(0) = c^0,\ c(\infty) = c_0.$$

2. The problem (1.6) and (1.7) was solved numerically by allowing the phase permeabilities and capillary pressure reach stationary values using model functions described by the

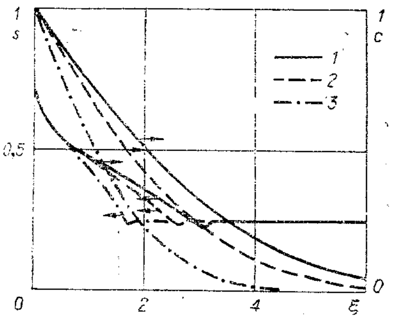

Fig. 1

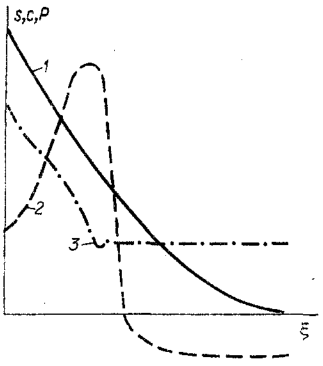

Fig. 2

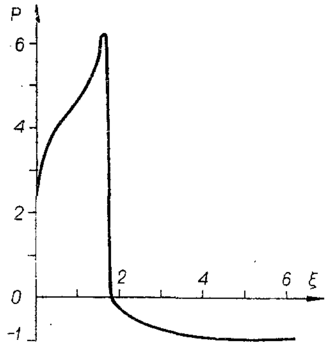

Fig. 3

expression

$$a(c) = \Gamma\varphi(c),\ \varphi(c) = bc,$$

$$f_1 = \left(\frac{s-0.2}{0.8}\right)^3\left(\frac{l}{a\,(c)+l}\right)^\beta,\quad f_2 = \left(\frac{0.8-s}{0.6}\right)^3,$$

$$P_c = \begin{cases} A\,(c-c^*)\,(s-0.2)^{-2}, & c > c^*, \\ A\,(c-c^*)\,(0.8-s)^{-2}, & c < c^*. \end{cases}$$

In addition, the following values of the parameters were used in the calculations:

$$\beta = 1,\ m = 0.2,\ l = 200,\ \Gamma = 1,\ b = 0.5,\ A = 1,\ \mathrm{P} = 1,$$
$$k = 1\mathrm{D},\ \mu_1 = 1\ \mathrm{cP}\quad \mu_2 = 3\ \mathrm{cP}\quad c^* = 0.3.$$

Some of the results of the calculations are shown in Fig. 1, where the values $D/a_*^2 = 1$, 0.7, and 0.3 correspond to the pairs of curves 1-3. In comparing with well-known results for pure capillary permeation [1-3] and results obtained previously for permeation of a hydrophilic specimen by a solution with an active ingredient [6], two circumstances stand out: the presence of a minimum in the water saturation distribution and concentration of a water saturation wave in the region of concentrations of the active ingredient exceeding a threshold value c* (the latter reflects the leading role of diffusion in permeation of a hydrophobic specimen). Both of the results indicated are comparatively easily interpreted qualitatively. In order to make such an interpretation, we replace Eq. (1.6) by a simpler model equation

$$\xi\frac{ds}{d\xi} = -2\alpha\frac{d}{d\xi}\left(\frac{dP_c}{d\xi}\right). \tag{2.1}$$

Assume, further, that s decreases significantly compared to S° for the same values of ξ, for which c > c*. Then, the corresponding values of P_c will exceed the values of the capillary pressure at the inlet ($\xi = 0$) and especially in the unperturbed zone ($\xi \to \infty$). Thus, the expected distribution $P_c(\xi)$ must have the form shown in Fig. 2 (curve 2); then, the saturation distribution, according to (2.1), must have a minimum (curve 3) and curve 1 illustrates the concentration distribution. Actual calculations give the same picture (Fig. 3 shows the capillary pressure distribution corresponding to curve 3 in Fig. 1). From the physical point of view, the presence of a maximum in the curve $P_c(\xi)$ has a simple meaning: in order that the process of capillary permeation proceed, it is necessary that the capillary pressure inside the specimen be higher than on the extremal surface of the specimen. The region of the maximum in capillary pressure acts like a pump, drawing in water and driving off oil. The appearance of a minimum in the saturation distribution is in fact related to the action of this pump: water from the depth of the specimen is drawn into the zone with maximum capillary pressure.

The fact that capillary permeation is possible, if the capillary pressure inside the specimen exceeds the capillary pressure at the inlet, shows that the effective depth of capillary impregnation of a hydrophobic specimen is of the same order of magnitude as the penetration depth of the isotherm c = c* and, for this reason, depends in a decisive manner on the rate of diffusion transport.

Thus, in choosing surfactants that can make a surface hydrophilic (in contrast to surfactants that simply increase the wettability of the rock by oil), special attention should be paid to the magnitude of the diffusion coefficient of the active substance.

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DOUBLE EXPLOSION IN A PERFECT GAS

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Strong-explosion problems have now been examined in some detail. An analytic solution has been obtained [1], the self-modeling equations have been examined [1-3] and approximate and numerical methods have been developed [3-10]. It is of interest to apply a similar process to a double explosion which can be formulated as follows in the simplest case. At time $t = -t_0$ there is an instantaneous release of energy E_1^0 on a plane, on a line, or at a point (symmetry parameter ν respectively 1, 2, and 3). At time $t = 0$, there is a second explosion of energy E_2^0 at the center of symmetry of the first explosion. We assume that the adiabatic parameters γ behind the two explosion-wave fronts are identical, while the density ρ_0 of the unperturbed gas is constant. The first wave is considered as strong. It is obvious that a self-modeling solution [1] applies to the flow between the two fronts before they fuse ($t \leqslant t_c$) and at a large time after fusion ($t \gg t_c$). The non-self-modeling flow behind the second shock wave can be described by numerical methods [4-6, 8-10]. Here we neglect the effects of dissipation, ionization, and radiation emission on the strong explosion. In spite of the simplicity of the formation, the problem is important to explosion theory, since there are two new control parameters $\lambda = E_2^0/E_1^0$ and t_0 by comparison with the classical solution.

After the second explosion and before the fusion ($t \leqslant t_c$), the flow in the region between the fronts is characterized by E_1^0, ρ_0, γ, ν, r, t and therefore is dependent on the single dimensionless variable $\eta = r[E_1t^2/\rho_0]^{-1}/(\nu+2)$. To describe the flow behind the second front, it is necessary to have the parameters E_2^0 and t_0, because here the flow ceases to be self-modeling and is dependent on the two independent variables η and $\tau = t/t_0$, as well as on the parameters λ^0, ν, γ. Therefore, the calculation must be performed for each particular λ^0, while t_0 is considered as the time scale, by analogy with an explosion with counterpressure. We consider finite $t_0 < \infty$. In that case, the second wave always catches up with the first, since the latter is always strong and any C_+ characteristic catches up with the front in a finite time. The occurrence of a double configuration of waves that do not fuse in practice is related to the counter pressure in the unperturbed gas, which results in a negative phase behind the first wave.

The subscripts $1*$ and $2*$ denote the quantities at the fronts of the first and second shock waves respectively. Subscript $*$ denotes quantities at the front of the wave formed by fusion in the double explosion (resultant wave).

1. Self-Modeling Stages. During the initial instants ($t \ll t_0$) after the second point

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