13. A. G. Kasatkin, Basic Processes and Equipment of Chemical Technology [in Russian], Moscow (1971).
14. H. L. Toor and J. M. Marchello, Am. Inst. Chem. Eng. J., 4, No. 1, 97-101 (1958).

TWO-DIMENSIONAL FILTRATIONAL FLOW IN THE DISPLACEMENT OF PETROLEUM FROM BEDS IN A BOREHOLE SYSTEM

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An approximate analytical method is developed for calculating plane filtrational flows of a two-phase multicomponent incompressible liquid in a porous medium. The method is based on the assumption that the streamlines in multiphase multicomponent filtration are the same as in the flow of homogeneous incompressible liquid. On this assumption, the initial problem reduces to solving the two-dimensional problem of the filtration of a homogeneous incompressible liquid and the one-dimensional problem of multiphase displacement. Accurate solutions of both problems are obtained. The integral characteristics of the flow are calculated. As an example, the displacement of petroleum by means of an aqueous polymer solution is considered.

Consider the two-dimensional filtration problem describing the displacement of petroleum by solvents, water, and reagent solutions in a borehole system, which reduces to a system of equations of two-phase filtration with interphase mass transfer [1]. Such filtrational flows are calculated by means of the approximate method of rigid current tubes, on the basis of the assumption that the streamlines in two-phase displacement are the same as in the filtration of homogeneous fluid [2]. Several current tubes are isolated here, and the process of one-dimensional displacement in each one is analytically calculated [3]. It was shown in [4, 5] that, even with a large difference in viscosity between the displacing and displaced phases, the streamlines are not much deformed in the course of displacement. This offers the possibility of using the given assumption in developing numerical methods of multiphase multicomponent displacement [6].

On the assumption of rigid streamlines, the solution of the two-dimensional system of equations of two-phase multicomponent filtration reduces to solving two independent problems: the plane problem of the filtration of a homogeneous incompressible liquid in a borehole system and the one-dimensional problem of two-phase displacement in a current tube of variable cross section with a specified pressure difference. In [7], approximate solutions of each of these problems were found.

In the present work, accurate solutions of both problems are obtained, and on this basis an analytical method of calculating the two-dimensional displacement of petroleum by slugs (finite portions) of active impurity carried through the bed by water is developed. This method may be used in calculating groundwater filtration, in geochemistry, hydrology, and reclamation, in water-pressure development of gas fields, in the displacement of petroleum by gases, solvents, and slugs, and in describing the noninertial and filtrational heterogeneous flows encountered in chemical technology [8].

Formulation of the Problem

Consider the two-dimensional displacement of petroleum by a reagent slug carried through the bed by water. In the large-scale approximation, this process is described by the system of equations [9, 10]

I. M. Gubkin Institute of Petroleum and Gas. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 61, No. 1, pp. 103-111, July, 1991. Original article submitted June 11, 1990.

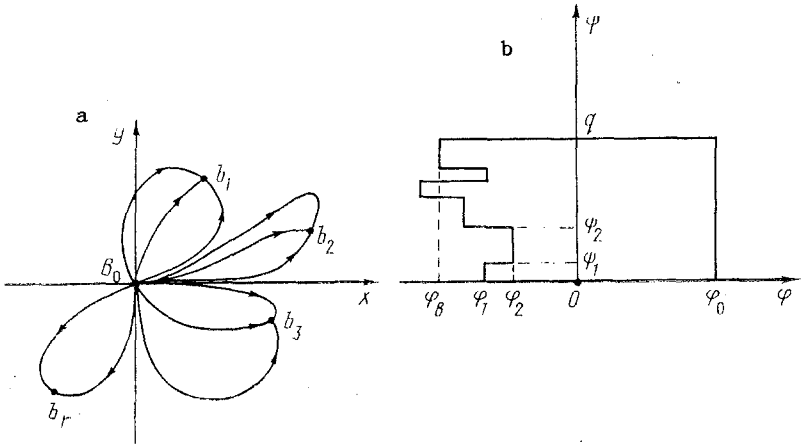

Fig. 1. Filtration region: a) in the x, y plane; b) in the φ, ψ plane.

$$m\frac{\partial s}{\partial t}+w_x\frac{\partial F(s,\ c)}{\partial x}+w_y\frac{\partial F(s,\ c)}{\partial y}=0; \tag{1}$$

$$m\frac{\partial}{\partial t}(cs+\zeta(c)(1-s)+a(c))+w_x\frac{\partial}{\partial x}(cF+\zeta(1-F))+$$
$$+w_y\frac{\partial}{\partial y}(cF+\zeta(1-F))=0; \tag{2}$$

$$w_x=-\Pi(s,\ c)\,\partial P/\partial x,\ w_y=-\Pi(s,\ c)\,\partial P/\partial y; \tag{3}$$

$$\frac{\partial}{\partial x}\left(\Pi\frac{\partial P}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Pi\frac{\partial P}{\partial y}\right)=0; \tag{4}$$

$$\Pi(s,\ c)=k\left(\frac{f_0(s,\ c)}{\mu_0}+\frac{f_w(s,\ c)}{\mu_w}\right).$$

Equations (1) and (2) are the balance equations of the water and impurity; Eq. (3) is a generalized form of Darcy's law, and Eq. (4) is a consequence of the incompressibility of the total flow.

The chemical inundation in a bed with injection borehole b_0 and auxiliary boreholes b_j, j - 1, ℓ, is investigated (Fig. 1a). The boreholes are assumed to be holes of small radius r_c. The problem of petroleum displacement by a slug of chemical reagent corresponds to the following initial and boundary conditions [1]

$$t=0:\ s=s_0,\ c=0;\ F(s)|_{b_0}=1;\ \begin{cases}c|_{b_0}=c^0,\ 0<t<t_0;\\ c|_{b_0}=0,\ t>t_0,\end{cases} \tag{5}$$

$$P|_{b_0}=P_0(t),\ P|_{b_j}=P_j(t). \tag{6}$$

Description of Streamlines

Consider the auxiliary problem of the filtration of homogeneous incompressible liquid in the same borehole system b_0, b_j as in the initial formulation. The system of equations describing this process consists of Darcy's law and the continuity equation [10]

$$u_x=-\partial\varphi/\partial x,\ \ u_y=-\partial\varphi/\partial y,\ \ \varphi=kP/\mu_i; \tag{7}$$

$$\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}=0. \tag{8}$$

The boundary conditions for Eqs. (7) and (8) take the form in Eq. (6). The existence of a function at ψ such that

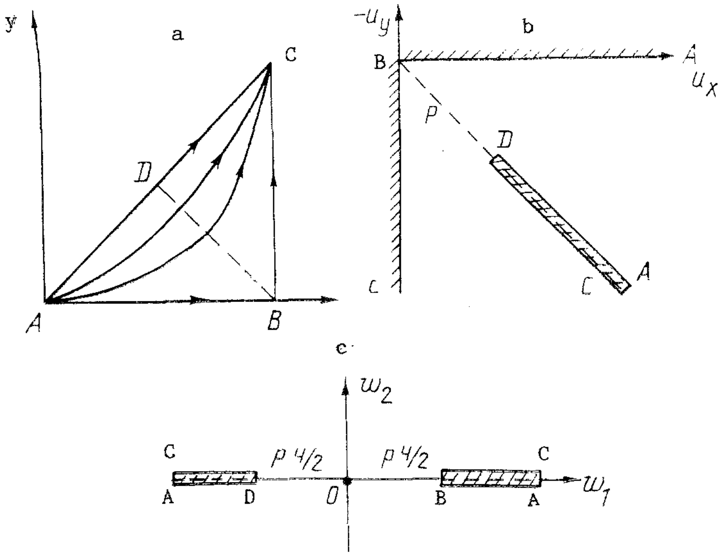

Fig. 2. Solution of the problem of filtration in a symmetry element of a five-point borehole grid by the hodograph method: a) plane z; b) plane u; c) plane $\omega = u^4 + p^4/2$.

$$u_x = \partial\psi/\partial y,\quad u_y = -\partial\psi/\partial x \tag{9}$$

follows from Eq. (8). The complex potential W and complex filtration rate u are introduced as analytical functions of the complex variable $z = x + iy$ [10, 11]

$$W = -\varphi + i\psi,\quad u = u_x - iu_y = dW/dz. \tag{10}$$

Below, it will be necessary to know the dependence of the Jacobian of the transformation $(x, y) \to (\varphi, \psi)$ on φ and ψ (Fig. 1)

$$|u|^2(\varphi,\ \psi) = u\bar{u} = u_x^2 + u_y^2. \tag{11}$$

For the injection borehole b_0 and the auxiliary borehole b_1 at points $(-a, 0)$ and $(a, 0)$ of the axis Ox (Fig. 1), using the well-known expression for a complex potential [12], it is found that

$$|u|^2(\varphi,\ \psi) = \frac{q^2}{4\pi^2a^2}\left(\operatorname{ch}\frac{2\pi}{q}(\varphi - c) - \cos\frac{2\pi}{q}\psi\right)^2;$$
$$q = \frac{\pi k(P_0 - P_1)}{\mu_t \ln(2a/r_c)},\quad c = \frac{k}{2\mu_l}(P_0 + P_1). \tag{12}$$

The problem of filtration in a symmetry element of a five-point borehole grid [7] may be solved by the hodograph method [13]. In this transformation, the filtration region (Fig. 2a) is conformally mapped onto the fourth quadrant with a cut along the bisector on the plane of the complex variable u (Fig. 2b). Then, using a power-law mapping, the initial formulation reduces to the problem of the influx at an isolated crack (Fig. 2c), the solution of which is known. Inverse transformation gives

$$|u|^2(\varphi,\ \psi) = \frac{p^2}{\sqrt{2}}\left[\operatorname{ch}\frac{8\pi\varphi}{q} - \cos\frac{8\pi\psi}{q}\right]^{1/2}; \tag{13}$$

$$p = \frac{q}{\sqrt{2}\,\pi a}\int_1^\infty \frac{d\lambda}{(\lambda^4 - 1)^{1/2}}.$$

Using Eqs. (7) and (9), Eqs. (1)-(4) are rewritten in the coordinate system (φ, ψ):

$$m\frac{\partial s}{\partial t}-(u_x w_x+u_y w_y)\frac{\partial F}{\partial \varphi}+(w_y u_x-w_x u_y)\frac{\partial F}{\partial \psi}=0; \tag{14}$$

$$m\frac{\partial}{\partial t}(cs+\varsigma(1-s)+a)-(u_x w_x+u_y w_y)\frac{\partial}{\partial \varphi}(cF+\varsigma(1-F))+$$
$$+(w_y u_x-w_x u_y)\frac{\partial}{\partial \psi}(cF+\varsigma(1-F))=0; \tag{15}$$

$$w_x=\Pi u_x\frac{\partial P}{\partial \varphi}+\Pi u_y\frac{\partial P}{\partial \psi},\quad w_y=\Pi u_y\frac{\partial P}{\partial \varphi}-\Pi u_x\frac{\partial P}{\partial \psi}; \tag{16}$$

$$\frac{\partial}{\partial \varphi}\left(\Pi\frac{\partial P}{\partial \varphi}\right)+\frac{\partial}{\partial \psi}\left(\Pi\frac{\partial P}{\partial \psi}\right)=0. \tag{17}$$

If the pressure change in the direction perpendicular to the streamline may be neglected, it may be assumed in Eqs. (14)-(17) that

$$\partial P/\partial \psi=0. \tag{18}$$

Taking this into account, Eq. (17) is integrated with respect to φ:

$$\Pi\frac{\partial P}{\partial \varphi}=H(\psi,\ t). \tag{19}$$

Substituting Eqs. (18) and (19) into Eq. (16), it is found that

$$w_x=Hu_x,\quad w_y=Hu_y. \tag{20}$$

Thus, in view of Eq. (18), the vectors u and w are collinear, which is equivalent to the assumption of constancy of the streamlines $\psi(x,\ y)$ = const along which filtration occurs.

Using Eq. (20), Eqs. (14) and (15) take the form

$$m\frac{\partial s}{\partial t}-H(\psi,\ t)|u|^2\frac{\partial F}{\partial \varphi}=0; \tag{21}$$

$$m\frac{\partial}{\partial t}(cs+\varsigma(1-s)+a)-H|u|^2\frac{\partial}{\partial \varphi}(cF+\varsigma(1-F))=0. \tag{22}$$

After the variable change (φ, t) → (ξ, τ), where

$$\xi(\varphi,\ \psi)=\int_{\varphi}^{\varphi_0}\frac{d\varphi'}{|u|^2(\varphi',\ \psi)},\quad \tau(\psi,\ t)=\int_0^t\frac{H(\psi,\ t')}{m}dt'. \tag{23}$$

Eqs. (21) and (22) take the form

$$\frac{\partial s}{\partial \tau}+\frac{\partial F}{\partial \xi}=0; \tag{24}$$

$$\frac{\partial}{\partial \tau}(cs+\varsigma(1-s)+a)+\frac{\partial}{\partial \xi}(cF+\varsigma(1-F))=0. \tag{25}$$

In this system and in Eqs. (21) and (22), ψ appears only as a parameter. The boundary conditions in Eq. (5) in the coordinates (ξ, τ) take the form

$$\tau=0{:}s=s_0,\ c=0;\ \xi=0{:}F=1;\ \begin{cases} c=c^0,\ 0<\tau<\tau(t_0,\ \psi)=\tau_0(\psi), \\ c=0,\ \tau>\tau_0(\psi). \end{cases} \tag{26}$$

The problem of displacement along the streamlines in Eqs. (24) and (25) with the boundary conditions in Eq. (26) is analogous to the one-dimensional problem of the displacement of petroleum by a slug of reagent [10, 14]. Suppose that the reagent is sorbed according to a linear law and is insoluble in petroleum

$$a=\Gamma c,\ \zeta=0.$$

Under these assumptions, Eqs. (24)-(26) has the solution [14]

$$\begin{gathered} s=s_0,\ c=0,\ D<\xi/\tau<\infty;\ s=s_2,\ c=0, \\ \frac{F_1}{F_s'(s,\ c^-)(s_1+\Gamma)}=D_1=\frac{F_2}{s_2+\Gamma}<\frac{\xi}{\tau}<D=\frac{F_2}{s_2-s_0}; \\ \xi/\tau=F_s'(s,\ c^0),\ c=c^0,\ \xi_0(\tau)<\xi<D_1\tau; \\ s(\xi,\ \tau)=F_s'(s^-,\ 0),\ \frac{F(s^-,\ 0)}{s^-+\Gamma}=\frac{F(s^+,\ 0)}{s^++\Gamma}; \\ \xi_0(\tau')/\tau'=F_s'(s^+,\ c^0),\ F(s^+,\ c_0)-F_s'(s^0,\ c^0)(s^++\Gamma)=1/\tau'. \end{gathered} \tag{27}$$

In this solution, there is an unperturbed flow zone in front of velocity front D; there is water-pressure rotation with constant saturation s_2 behind this front up to velocity front D_1; there is a centered saturation wave in the zone of the slug behind the front D_1 to the back of the slug ξ_0/τ and a simple wave beyond that. The values in front of – $\xi_0(\tau')$, $s^+(\tau')$ – and behind $s^-(\tau')$ – the rear of the slug are related by the Hugoniot conditions. The trajectory $\xi_0(\tau')$ and the saturation of s^+ are specified as parametric dependences $\tau'(s^+)$ and $\xi_0(s^+)$. The mapping of the solution on the (F, s) plane, the form of the dependence of s and c on ξ/τ at fixed time τ', and the trajectories of velocity-front motion are shown in Fig. 3a, b, c, respectively.

The unknown dependences $H(\psi,\ t)$, $\tau(\psi,\ t)$ are determined from the boundary conditions in Eq. (6). Integration of Eq. (19) gives

$$P(\varphi,\ \psi,\ t)=\int_{\varphi}^{\varphi_0}\frac{Hd\varphi'}{\Pi(s(\varphi',\ \psi,\ t),\ c(\varphi'\ \psi,\ t))}+\text{const}. \tag{28}$$

Suppose that streamline ψ runs from the injection borehole to auxiliary borehole j (Fig. 1). In view of Eq. (27), the total phase mobility Π along this line, which depends on s and c, is a function of ξ, τ, and τ_0. The pressure difference ΔP_j between the boreholes is found from Eqs. (6) and (28)

$$\Delta P_j(t)=H(\psi,\ t)F(\psi,\ \tau,\ \tau_0),\ \Gamma=\int_{\varphi_j}^{\varphi_0}\frac{d\varphi}{\Pi(\xi(\varphi,\ \psi),\ \tau,\ \tau_0)}. \tag{29}$$

From the definition of τ

$$H(\psi,\ t)=m\partial\tau/\partial t. \tag{30}$$

Substituting this relation into Eq. (29), a differential equation for $\tau(\psi,\ t)$ is obtained

$$\partial\tau/\partial t=\Delta P_j(t)/m\Gamma(\psi,\ \tau,\ \tau_0), \tag{31}$$

where ψ appears as a parameter. After variable separation and the use of the initial condition $\tau(0,\ \psi)=0$, it is found that

$$m\int_0^{\tau}\Gamma(\psi,\ \tau',\ \tau_0)\,d\tau'=\int_0^{t}\Delta P_j(t')\,dt'. \tag{32}$$

The substitution of $\tau=\tau_0$, $t=t_0$ here gives $\tau_0(\psi)$.

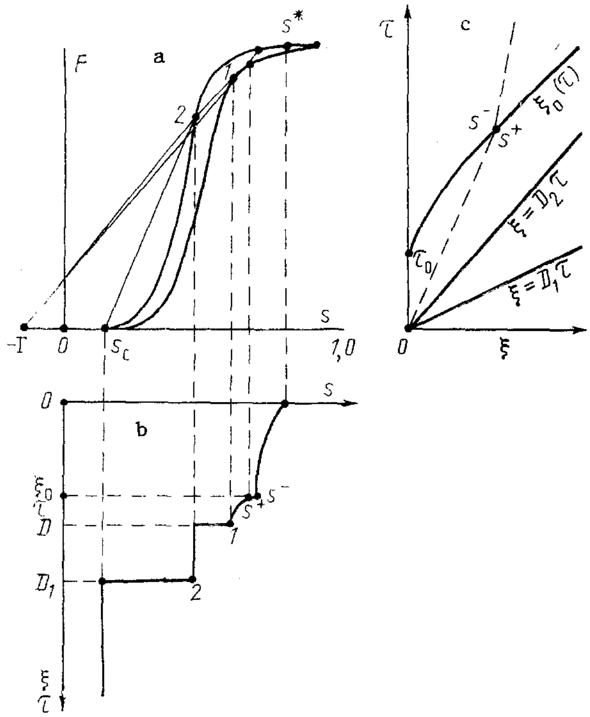

Fig. 3. Solution of the one-dimensional problem of the displacement of petroleum by a slug of reagent solution: a) in the phase plane of the system; b) profile of the saturation distribution; c) in the plane ξ, τ.

Thus, the accurate solution of the problem of two-dimensional displacement under these assumptions is constructed as follows. First, the dependence $\xi(\varphi, \psi)$ is found from Eq. (23). The function $|u|^2(\varphi, \psi)$ used here is defined by Eqs. (12) and (13) for various cases. Then the solutions $s(\xi, \tau, \tau_0)$, $c(\xi, \tau, \tau_0)$ of Eq. (27) are constructed. The dependence $\tau(\psi, t)$ is found from Eq. (32) and $H(\psi, t)$ from Eq. (30). Then the pressure $P(\varphi, \psi, t)$ is calculated, and transition to the (x, y) plane is possible.

Calculating the Integral Characteristics of the Flow

The important integral characteristics of the two-phase flow may be calculated without transition to the (x, y) plane. Consider an arbitrary curve ℓ connecting points 1 and 2 on the filtration plane. The flow rate Q_{12} through this curve per unit bed thickness is found from the formula

$$Q_{12}=\int_1^2 w_n dl.$$

Using the identity $u_n d\ell = d\psi$ [8], it follows from this relation and Eq. (20) that

$$Q_{12}=\int_1^2 Hu_n dl=\int_{\psi_1}^{\psi_2} H(\psi, t)d\psi. \quad (33)$$

Thus, H is the liquid flow rate in a single streamline, referred to the bed thickness. Taking account of Eq. (30), both sides of Eq. (33) are integrated from 0 to t

$$T_{12}(t)=\int_{\psi_1}^{\psi_2}\tau(\psi, t)d\psi.$$

Here $T_{12}(t)$ defines the liquid volume transferred between streamlines 1 and 2 at time t, referred to the bed thickness. The total volume of liquid pumped into the bed T(t) and the volume of liquid $T_j(t)$ obtained from borehole j at time t expressed in bed volumes Ω are

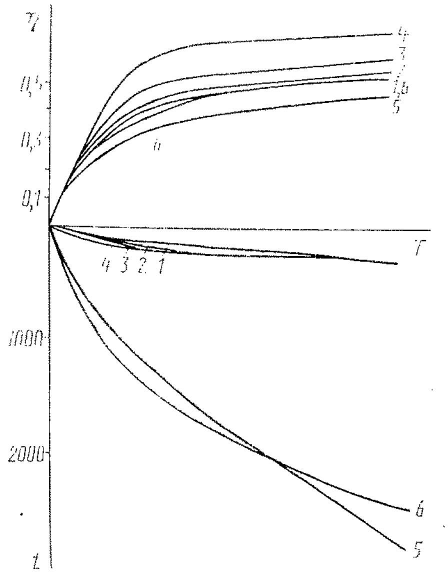

Fig. 4. Dependence of the petroleum yield η and injection time t on the volume of injected liquid T. Single-layer bed: 1) water; 2) $\Omega_0 = 0.2\Omega$, c = 0.05%; 3) $\Omega_0 = 0.1\Omega$, c = 0.1%; 4) $\Omega_0 = 0.05\Omega$, c = 0.2%; three-layer bed: 5) water; 6) $\Omega_0 = 0.1\Omega$, c = 0.1%; t, day.

$$T(t) = mh\int_0^q \tau(\psi,\ t)\,d\psi/\Omega,\quad T_j(t) = mh\int_{\psi_{j-1}}^{\psi_j} \tau(\psi,\ t)\,d\psi/\Omega\ (j = 1,\ l);$$

$$\psi_0 = 0,\quad \psi_j = \sum_{k=1}^{j} q_k.$$

Using the physical meaning of F(s, c), an expression is obtained for $\eta_j(t)$, the total petroleum output through the j-th borehole at time t expressed in terms of the initial petroleum reserves

$$\eta_j(t) = \int_{\psi_{j-1}}^{\psi_j}\int_0^t (1-F)|_{\varphi=\varphi_j} H(\psi,\ t')\,dt'd\psi/(1-s_0)\,\Omega.$$

Example of Calculation

The two-dimensional displacement of petroleum by a polymer slug from a homogeneous bed is considered in conditions corresponding to the Chaivo-More (Sakhalin) field [15]. The thickness, permeability, and porosity of the bed are h = 52.3 m, k = 1.35 μm^2, and m = 0.23, respectively. The displacement from a symmetry element of a five-point borehole grid with a distance of 150 m between adjacent injection and auxiliary boreholes ($a = 150/\sqrt{2} = 107$ m) and a pressure difference between them ΔP = 2 MPa is calculated. The initial water saturation is $s_0 = 0.35$; the viscosity of petroleum and water $\mu_0 = 6.5$ mPa·sec, $\mu_w = 0.35$ mPa·sec. The phase permeabilities are

$$f_w(s) = 1.5(s-0.2)^{2.5},\quad f_0(s,\ c) = 2.5(s^*(c)-s)^{1.53};$$
$$s^*(c) = 0.74+4c\quad (0 \leqslant c \leqslant 0.2\%).$$

The Buckley—Leverett functions corresponding to the displacement of petroleum by a polymer solution — the curve of F(s, c) — and the displacement of petroleum by water in the presence of irreversibly held polymer in the porous medium — the curve of $F^a(s, 0)$ in Fig. 3a — are calculated taking account of the drag factor

$$F(s,\ c) = (1+f_0(s,\ c)\,\mu_w/f_w(s)\,\mu_0)^{-1};$$
$$F^a(s,\ 0) = (1+(f_0(s,\ 0)\,\mu_w(f_w(s,\ 0)\,\mu_0)/(R(c)\,\mu_w/\mu_p(c)))^{-1};$$
$$R(c) = 0.3+32c,\quad \mu_p(c) = (0.9+10c)\,\mu\ \mathrm{Pa\cdot sec}\quad (0 \leqslant c \leqslant 0.2\%).$$

The sorption isotherm is linear with a coefficient $\Gamma = 0.12$; the polymer sorption is irreversible.

The dependence of the petroleum yield η expressed in terms of the initial reserves and the injection time t on the volume of injected liquid T, expressed in terms of the bed volume, is shown in Fig. 4. The displacement from a single-layer bed corresponds to curves 1-4. Curves with higher numbers correspond to larger impurity concentration in the slug; the petroleum yield corresponding to the given volume of injected liquid is also larger. Thus, when T = 1, the petroleum yield corresponding to pure water injection (curve 1) is 0.38; the petroleum yield with an impurity concentration c = 0.2% in the slug (curve 4) is 0.57. When T < 3, the time corresponding to a given T increases with increase in the impurity concentration in the slug, and then equalizes; after T = 3, it begins to decrease, since at this point the slug reaches the extractional borehole along the basic streamline. At T = 1, these times are 178 and 229 days for curves 1 and 4, respectively.

The above method may be used to calculate the displacement from a bed with laminar inhomogeneity. Curves 5 and 6 in Fig. 4 correspond to the displacement of petroleum by water and a slug of active impurity from a three-layer bed with layer permeabilities of 0.64, 1.35, and 0.1 μm^2 and thicknesses of 11, 52.3, and 14.7 m, respectively. The petroleum yield of the laminar bed is less, and the time corresponding to the given injection volume is greater, than for a homogeneous bed. This is associated with the large hydraulic drag of the relatively impermeable layers and also with the arrival of the displacing water at the output borehole along a fast streamline in the highly permeable beds, after which most of the injected water runs along this streamline and does not make a significant contribution to the petroleum yield. At T = 1, the petroleum yield is $\eta = 0.33$ in the case of pure water (curve 5) and $\eta = 0.40$ with a polymer concentration in the slug c = 0.1% (curve 6).

CONCLUSIONS

Assuming constancy (rigidity) of the streamlines, the problem of two-dimensional displacement in a borehole system admits of accurate solution. In the potential—current-function (φ, ψ) coordinate system, the two-dimensional problem may be regarded as a set of one-dimensional problems. The construction of their solutions and the calculation of the integral flow characteristics — the total flow rate and the flow rate of each phase through the boreholes — from the solution of the auxiliary problem of incompressible-liquid filtration only requires knowledge of the Jacobian of the transformation (x, y)—(φ, ψ). Calculation of the two-dimensional displacement of petroleum by a reagent slug from a bed of laminar inhomogeneity in a symmetry element of a five-point borehole grid shows that the above approach takes account of both the degree of displacement and the coverage of the plate by the treatment.

NOTATION

x, y, coordinates in a plane; t, time; m, porosity; s, saturation of aqueous phase; P, pressure; c, $\xi(c)$, impurity concentration in water and petroleum; $a(c)$, concentration of sorbed impurity; F(s, c), Buckley—Leverett function; w_x, w_y, components of total filtration rate; $\Pi(s, c)$, total phase surface; k, permeability of porous medium; μ_0, μ_w, viscosity; $f_0(s, c)$, $f_w(s, c)$, relative phase permeabilities of petroleum and water, respectively; μ_ℓ, viscosity of homogeneous liquid; φ, potential of its flow; u_x, u_y, flow-velocity components of homogeneous liquid; h, bed thickness; q, q_j ($j = 1, \ell$), flow rates through injection and output boreholes; φ_j, potential at j-th borehole; $\mu_p(c)$, viscosity of polymer solution; R(c), resistance at polymer concentration c; Ω_0, slug volume.

LITERATURE CITED

1. V. L. Danilov and R. M. Kats, Hydrodynamic Calculations of the Mutual Displacement in a Porous Medium [in Russian], Moscow (1980).
2. M. Masket, Physical Principles of Petroleum-Extraction Technology [Russian translation], Leningrad (1953).
3. V. I. Kuranov and S. A. Kundin, Solution of the Problem of Petroleum Displacement by Water for a Five-Point Element by the Rigid-Current-Tube Method [in Russian], Moscow (1964).
4. J. C. Martin and R. E. Wegner, Trans. AIME, 267, 313-323 (1979).

5. J. C. Martin, P. T. Woo, and R. E. Wegner, J. Pet. Tech., No. 2, 151-153 (1973).
6. B. Wang, L. W. Lake, and G. A. Pope, SPE 10,290 Presented at the SPE-AIME 56th Annual Fall Meeting, San Antonio (1981).
7. N. M. Glogovskii, A. B. Zolotukhin, and S. V. Sapozhnikova, in: Physicochemical Methods of Increasing the Petroleum Yield of Beds. Collection of Scientific Works of the I. M. Gubkin Moscow Institute of Petroleum and Gas [in Russian], No. 181, Moscow (1985), pp. 15-32.
8. R. I. Nigmatulin, Dynamics of Multiphase Media [in Russian], Part 2, Moscow (1987).
9. P. G. Bedrikovetskii, M. V. Lur'e, and M. V. Filinov, Inzh.-Fiz. Zh., 43, No. 4, 684-685 (1982).
10. G. I. Barenblatt, V. M. Entov, and V. M. Ryzhik, Fluid Motion in Natural Beds [in Russian], Moscow (1984).
11. M. A. Lavrent'ev and B. V. Shabat, Methods in the Theory of Functions of a Complex Variable [in Russian], Moscow (1973).
12. K. S. Basniev, A. M. Vlasov, I. N. Kochina, and V. M. Maksimov, Underground Hydraulics [in Russian], Moscow (1973).
13. M. I. Gurevich, Theory of Ideal-Fluid Jets [in Russian], Moscow (1961).
14. P. G. Bedrikovetskii, Dokl. Akad. Nauk SSSR, 262, No. 1, 49-53 (1982).
15. P. G. Bedrikovetskii and A. M. Polishchuk, in: Collection of Scientific Proceedings of the All-Union Petroleum and Gas Scientific-Research Institute [in Russian], No. 83 (1983), pp. 202-214.

PARTICLE GRANULATION IN FLUIDIZED BED

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UDC 66.099.2:661.183.6

A mechanism of particle granulation in a wet fluidized bed is proposed on the basis of experimental data, and test calculations are performed.

The rheological transformations of a wet disperse medium under the action of vibration underlie the intensification of such technological processes as filtration, drying, granulation, and transportation [1]. Common to these processes is the granulation of material in a wet grainy medium moving under the action of spatial vibration. Granulation has been most investigated at elements introduced in the form of specially prepared small lumps [2] or liquid drops [3-5], which determines the disperse composition of the granules obtained. However, these experiments do not address the question of the granulometric composition of the filler with uniform moisture content of the particles over the whole layer in a vertically vibrating container, corresponding, in particular, to drying in a fluidized bed (Fig. 1a). In determining the granulometric composition of a uniformly wet mixture in a vibrating container, serious methodological difficulties arise. Therefore, taking into account that the size of the new particles in vibrogranulators of various types is $\sim 10^{-3}$ m [5-8], aerodynamic forces in a fluidized bed of such particles may be neglected [3], and the gas-permeable bottom of the container is replaced by a set of screens (diameter 200 mm) from a standard sifting unit. This system is an analog of a fluidized unit with convective heat-carrier supply. However, special investigations show that a similar granulometric composition of the disperse mass is also observed in apparatus with a gas-permeable bottom, which means that the results obtained may be extended to apparatus with conductive heat supply.

The error of the given method is determined by the ratio of granulation and screening rates. Since the relaxation time of the capillary processes ($\sim 10^{-3}$ sec)* at a distance of

*Estimate based on the data of [9].

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