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HEAT AND MASS TRANSFER IN DISPERSE MEDIA

INVERSE THERMAL EFFECT OF DISPLACED LIQUID IN A POROUS MEDIUM

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The inverse thermal effect of the liquid displaced in a porous medium is investigated, with the effect occurring because of the fact that, with the thermal conductivity being neglected, temperature jumps move with the speed of convective heat transfer. In piston displacement, the front moves with a true velocity which several times exceeds those of filtration and of convective heat transfer. Due to the faster advance of the displacement front, a special zone is formed, in which the process of inverse thermal effect of the displaced liquid on the displacing one is observed.

The results of measurements of a barothermal effect in oil beds are used for determining workable and watered intervals, intervals of motion outside a column, thermal probing of beds, and for solving other problems of production. Special highly sensitive thermometers developed for these purposes are used together with other methods and lie at the basis of the methods of controlling oil- and gas-field development. Among the most promising problems of sounding is the forecast of the encroachment of beds with injection water; however, such kind of problems have not been solved as yet. The difficulties in the development of the theory of the barothermal effect on water–oil displacement consist of the necessity of taking into account complex processes at the front of flooding, where miscible displacement occurs. The most effective method of simplifying such problems is the assumption on a plane front of displacement (piston displacement), which can be realized with the aid of special additions to water.

It has been established earlier [1] that during the process of oil displacement in the zone of invasion a region appears in which the temperature field depends on the physical characteristics of the oil. This is the so-called zone of inverse effect of an oil-saturated region on a water-saturated one. As a result, an abnormal heating of water occurs, in view of which the study of this phenomenon is of particular interest. Below, for simplicity a linear geometry of flow is used, since it allows one to reveal the most important characteristic features of the barothermal effect in piston water–oil displacement.

The temperature field in a porous rod is described by the equation of barothermal effect, which, with the thermal conductivity and adiabatic effect being neglected, has the form

$$\frac{\partial T_i}{\partial t} + U_i \left(\frac{\partial T_i}{\partial x} + \varepsilon_i \frac{\partial P_i}{\partial x} \right) = 0 , \tag{1}$$

where $i = 1$ and 2 for water ($0 < x < R(t)$) and oil ($R(t) < x < L$), respectively.

The model of miscible displacement forecasts the presence of a front with a water-saturation jump from zero to a certain value of s_j. Calculations show that the magnitude of the saturation jump s_j depends on the ratio of the viscosities of water and oil $\mu = \mu_2/\mu_1$ and it changes from 0.5 to 0.8 on change in μ from 1 to 20. At a relative viscosity of the order of ten, changes in water saturation in the displacement zone are insignificant. The mean values of oil saturation in the displacement zone do not exceed 10%. Under such conditions, the model of piston displacement can be applied with a high degree of accuracy; it allows one to construct an analytical solution of the temperature problem.

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The rate of convective heat transfer U_i is defined in terms of the pressure field P_i by the formula

$$U_i = -\frac{c_i}{c_{mi}} \frac{k}{\mu_i} \frac{\partial P_i}{\partial x} . \quad (2)$$

The pressure field, in turn, is determined with the aid of the continuity equation and Darcy's, law. It is shown below that in the given problem one can avail oneself of a quasi-stationary approximation when the equations for pressure are assumed to be stationary and the time enters into the problem parametrically in terms of the displacement-front coordinate $R(t)$:

$$\frac{d^2 P_i}{dx^2} = 0 . \quad (3)$$

The distribution of pressure in a homogeneous porous rod having length L and permeability k, at the ends of which a constant difference of pressures P_0 is sustained, under the conditions of piston water–oil displacement with allowance for the equality of pressures and true velocities at the displacement front $x = R(t)$, is described by the dependences

$$P_1 = -\frac{P_0 \mu_1 x}{L\mu_2 - R\Delta\mu} + P_0 , \quad 0 < x < R ; \quad (4)$$

$$P_2 = -\frac{P_0 \mu_2 (x - L)}{L\mu_2 - R\Delta\mu} , \quad R < x < L , \quad (5)$$

where $\Delta\mu = \mu_2 - \mu_1$ is the difference between the viscosities of oil and water. Pressure on the right-hand side end of the rod is taken as the start of the reading, i.e., it is taken to be equal to zero. An equation for $R(t)$ results from allowance for the fact that the ratio of the rate of water–oil displacement to the filtration rate is equal to the porosity m:

$$\frac{dR}{dt} = \frac{1}{m} \frac{k}{\mu_i} \frac{\partial P_i}{\partial x} \bigg|_{x=R} = \frac{1}{m} \frac{k P_0}{L\mu_2 - R\Delta\mu} . \quad (6)$$

Equation (6) yields an expression which describes the position of the displacement boundary and satisfies the condition $R(0) = 0$:

$$R = \frac{L\mu_2}{\Delta\mu} - \sqrt{\frac{L^2 \mu_2^2}{\Delta\mu^2} - 2 \frac{k}{m\Delta\mu} P_0 t} . \quad (7)$$

When the displacement front attains the point $R = L$, the pressure distribution no longer depends on time:

$$P = \frac{P_0 (L - x)}{L} , \quad 0 < x < L . \quad (8)$$

The process of water–oil displacement from a porous rod of length L proceeds during the period of time

$$\tau = mL^2 \frac{\mu_1 + \mu_2}{2kP_0} . \quad (9)$$

The resulting equation for the displacement time allows one to determine more accurately the conditions of applicability of the quasi-stationary approximation used in the present work. It gives rather accurate results if the time needed for establishment of a pressure field due to piezoconductivity L^2/χ is much shorter than the displacement time τ, which is equivalent to the condition of small compressibility of a porous medium by a saturated liquid $\beta P_0 << 1$, which is satisfied with a high accuracy for a water- and oil-saturated porous medium (here $\chi = k/m\beta$).

For an oil-saturated zone, the solution of the temperature problem

$$\frac{\partial T_2}{\partial t} + U_2 \left(\frac{\partial T_2}{\partial x} + \varepsilon_2 \frac{\partial P_2}{\partial x} \right) = 0 \, , \quad T_2 \, (t = 0) = 0 \tag{10}$$

with allowance for the equalities

$$\frac{\partial P_2}{\partial x} = - \frac{P_0 \mu_2}{L\mu_2 - R\Delta\mu} \, , \quad U_2 = - \frac{c_2}{c_{\rm m2}} \frac{k}{\mu_2} \frac{\partial P_2}{\partial x} = \frac{c_2}{c_{\rm m2}} \frac{k}{\mu_2} \frac{P_0 \mu_2}{L\mu_2 - R\Delta\mu} \tag{11}$$

can be found by the method of characteristics that are described as

$$x = - \frac{c_2}{c_{\rm m2}} \frac{m}{\Delta\mu} \sqrt{L^2 \mu_2^2 - 2 \frac{k\Delta\mu}{m} P_0 t} + C \, , \tag{12}$$

in the form

$$T_2 = - \varepsilon_2 \frac{c_2}{c_{\rm m2}} \frac{\mu_2}{2\Delta\mu} m P_0 \ln \left(1 - 2 \frac{k\Delta\mu}{mL^2 \mu_2^2} P_0 t \right),$$

$$x \geq R = \frac{L\mu_2}{\Delta\mu} - \sqrt{\frac{L^2 \mu_2^2}{\Delta\mu^2} - 2 \frac{k}{m\Delta\mu} P_0 t} \, . \tag{13}$$

For the water-saturated zone, the solution of the temperature problem

$$\frac{\partial T_1}{\partial t} + U_1 \left(\frac{\partial T_1}{\partial x} + \varepsilon_1 \frac{\partial P_1}{\partial x} \right) = 0 \, , \quad T_1 \, (x = 0) = 0 \tag{14}$$

subject to

$$\frac{\partial P_1}{\partial x} = - \frac{P_0 \mu_1}{L\mu_2 - R\Delta\mu} \, , \quad U_1 = \frac{c_1}{c_{\rm ï1}} \frac{kP_0}{L\mu_2 - R\Delta\mu} \tag{15}$$

can also be found by the method of characteristics that are described as

$$x = - \frac{c_1}{c_{\rm m1}} \frac{m}{\Delta\mu} \sqrt{L^2 \mu_2^2 - 2 \frac{k\Delta\mu}{m} P_0 t} + C \, , \tag{16}$$

in the form

$$T_1 = \varepsilon_1 \frac{c_1}{c_{\rm m1}} \frac{\mu_1}{\Delta\mu} m P_0 \ln \left(1 + \frac{c_{\rm m1}}{c_1} \frac{\Delta\mu}{m} \frac{x}{\sqrt{L^2 \mu_2^2 - 2k\Delta\mu P_0 \frac{t}{m}}} \right),$$

$$x < R_1 \, (t) = \frac{c_1}{c_{\rm m1}} \frac{m}{\Delta\mu} \left(L\mu_2 - \sqrt{L^2 \mu_2^2 - 2k\Delta\mu P_0 \frac{t}{m}} \right). \tag{17}$$

Note that the dimensions of the region where Eq. (17) is applicable do not exceed those of the displacement zone $R_1(t) < R(t)$; therefore for the region $R_1(t) < x < R(t)$ it is necessary to construct the solution of the problem

$$\frac{\partial T_1}{\partial t} + U_1 \left(\frac{\partial T_1}{\partial x} + \varepsilon_1 \frac{\partial P_1}{\partial x} \right) = 0 \,, \quad T_1 \,(x = R\,(t)) = T_2\,(t) \,. \tag{18}$$

This solution has the form

$$T_1 = - \varepsilon_1 \frac{c_1}{c_{\text{m1}}} \frac{\mu_1}{2\Delta\mu} m P_0 \ln \left(\mu_2^2 L^2 - 2 \frac{k\Delta\mu}{m} P_0 t \right) + C_1 \,. \tag{19}$$

The characteristics of Eq. (18) which coincide with (16) make it possible to construct the solution of problem (18). For this purpose, having equated $R(t)$ from (7) to characteristic (16), we will express t in terms of the constant C which enters into Eq. (16):

$$t = \frac{m}{2kP_0\Delta\mu} \left[L^2 \mu_2^2 - \left(\frac{L\mu_2 - C\Delta\mu}{1 - \dfrac{c_1 m}{c_{\text{m1}}}} \right)^2 \right] . \tag{20}$$

Having substituted (20) into (19) and used the boundary condition of problem (18), we obtain an expression for the constant C_1, with the aid of which we will represent the unknown solution in the form

$$T_1 = \varepsilon_1 \frac{c_1}{c_{\text{m1}}} \frac{\mu_1}{\Delta\mu} m P_0 \ln \left(\frac{L\mu_2 - C\Delta\mu}{\left(1 - \dfrac{c_1 m}{c_{\text{m1}}} \right) \sqrt{L^2 \mu_2^2 - 2k\Delta\mu \dfrac{P_0 t}{m}}} \right) + T_2 \left\{ \frac{m}{2kP_0\Delta\mu} \left[L^2 \mu_2^2 - \left(\frac{L\mu_2 - C\Delta\mu}{1 - \dfrac{c_1 m}{c_{\text{m1}}}} \right)^2 \right] \right\} . \tag{21}$$

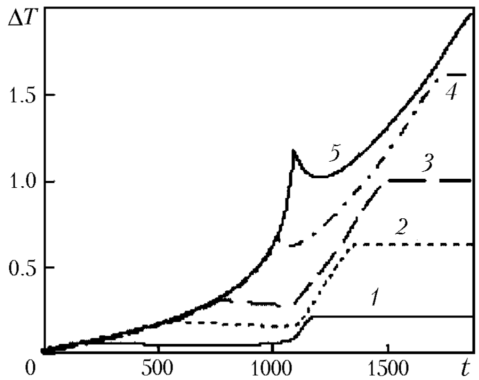
By excluding the constant C from (20) and (21) and substituting T_2 from (21) into (13), we obtain a finite expression for the temperature field in the region $R_1(t) < x < R(t)$:

$$T_1 = \varepsilon_1 \frac{c_1}{c_{\text{m1}}} \frac{\mu_1}{\Delta\mu} m P_0 \ln \left[\frac{c_{\text{m1}}}{c_{\text{m1}} - c_1 m} \left(\frac{L\mu_2 - x\Delta\mu}{\sqrt{\mu_2^2 L^2 - 2k\Delta\mu P_0 \dfrac{t}{m}}} - \frac{c_1}{c_{\text{m1}}} m \right) \right] -$$

$$- \varepsilon_2 \frac{c_2}{c_{\text{m2}}} \frac{\mu_2}{\Delta\mu} m P_0 \ln \left[\frac{c_{\text{m1}}}{c_{\text{m1}} - c_1 m} \left(1 - \frac{x\Delta\mu}{L\mu_2} - \frac{c_1}{c_{\text{m1}}} m \sqrt{1 - \frac{2k\Delta\mu}{mL^2 \mu_2^2 P_0 t}} \right) \right] . \tag{22}$$

The solution of the problem includes Eqs. (17) and (22) for the water-saturated zone and Eq. (13) for the oil-saturated one. According to Eq. (22), in the water-saturated zone a region $R_1(t) < x < R(t)$ appears, in which the temperature field is determined by the physical characteristics of oil and water. Consequently, there occurs a reverse thermal effect of the oil-saturated zone on the water-saturated one due to heat transfer through the porous-medium skeleton. The second term in Eq. (22) describes the contribution of this process. In the region indicated above, an abnormally high heating of water is observed. The phenomenon described is, in a sense, a thermal analog of the Vavilov–Cherenkov radiation which occurs during motion of charged particles with a velocity exceeding the velocity of electromagnetic waves in the medium.

The phenomenon of the reverse thermal effect originates for the following reasons. The rate of motion of temperature jumps coincides with that of convective heat transfer (2), which differs from the rate of filtration determined by Darcy's, law, the presence of the factor of which is equal to the ratio of the volumetric heat capacity of the liquid to the volumetric heat capacity of the porous medium [2]. Therefore the rate of convective transfer differs from the



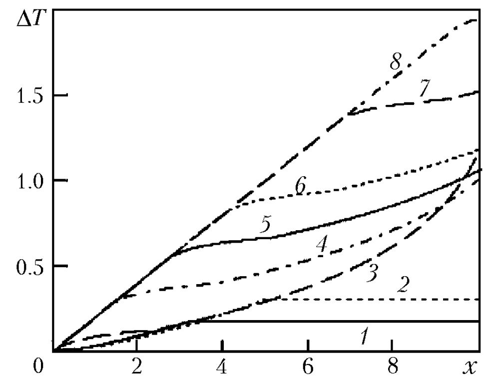


Fig. 1. Dependence of the magnitude of the barothermal effect on time at different points of the porous rod with different coordinates: 1) x = 1; 2) 3; 3) 5; 4) 8; 5) 10 m.

Fig. 2. Temperature distribution along the length of the porous rod at different times: 1) $t = 0.5\tau$; 2) 0.7τ; 3) τ; 4) 1.1τ; 5) 1.2τ; 6) 1.3τ; 7) 1.5τ; 8) 1.7τ.

rate of filtration: the former is smaller than the latter in the oil-saturated porous medium and vice versa in the water-saturated one. In the case of piston displacement, the front moves with a true velocity which is several times higher than both the rate of filtration and the rate of convective heat transfer. It is due to the faster advance of the displacement front that the process of the reverse thermal effect of a displaced fluid on the displacing one originates. The interest in investigation of this zone is also explained by the fact that the dimensions of the zone are relatively large.

By the time the water ceases to displace the oil, $t = \tau$, the temperature field in the porous rod is described by the expression

$$T_1 = \begin{cases} \varepsilon_1 \dfrac{c_1}{c_{\mathrm{m}1}} \dfrac{\mu_1}{\Delta\mu} m P_0 \ln \left(1 + \dfrac{c_{\mathrm{m}1}}{c_1 m} \dfrac{\Delta\mu}{\mu_1} \dfrac{x}{L} \right), \quad 0 < x < \dfrac{c_1}{c_{\mathrm{m}1}} mL \,; \\[2ex] \varepsilon_1 \dfrac{c_1}{c_{\mathrm{m}1}} \dfrac{\mu_1}{\Delta\mu} m P_0 \ln \left[\dfrac{c_{\mathrm{m}1}}{c_{\mathrm{m}1} - c_{1m}} \left(\dfrac{\mu_2}{\mu_1} - \dfrac{x\Delta\mu}{L\mu_1} - \dfrac{c_1}{c_{\mathrm{m}1}} m \right) \right] - \varepsilon_2 \dfrac{c_2}{c_{\mathrm{m}2}} \dfrac{\mu_2}{\Delta\mu} m P_0 \times \\[2ex] \times \ln \left[\dfrac{c_{\mathrm{m}1}}{c_{\mathrm{m}1} - c_{1m}} \left(1 - \dfrac{x\Delta\mu}{L\mu_2} - m \dfrac{c_1}{c_{\mathrm{m}1}} \dfrac{\mu_1}{\mu_2} \right) \right], \quad \dfrac{c_1}{c_{\mathrm{m}1}} mL < x < L \,. \end{cases} \tag{23}$$

According to (23), the zone of the reverse thermal effect by the time the displacement ceased at the values of the physical parameters indicated below (see Figs. 1–4) lies within the limits 2.4 m $< x <$ 10 m, i.e., it occupies a considerable portion of the porous-rod length (76%). As applied to oil beds, this means that on the breakthrough of water into the well, the registered effect of water heating will be the same as for oil. This imposes significant limitations on the employed thermometric technique of revealing the water-filled portions of the bed in oil wells. The effect of water heating will decrease only on termination of the stage of the "carrying-out of residual heating" from the zone of reverse thermal influence of the oil displaced. From this follows the practical importance of taking into account the phenomenon of reverse thermal effect of this oil when interpreting thermograms recorded in wells.

In order to find the temperature field for $t > \tau$, we will resort to the solution of the following simple problem:

$$\frac{\partial T}{\partial t} + U \left(\frac{\partial T}{\partial x} + \varepsilon_1 \frac{\partial P_1}{\partial x} \right) = 0 \,, \quad U = \frac{c_1}{c_{\mathrm{m}1}} \frac{k}{\mu_1} \frac{P_0}{L} \,, \quad T\,(x = 0) = 0 \,, \quad T\,(t = \tau) = T_1\,(x, \tau) \,. \tag{24}$$

This solution has the form

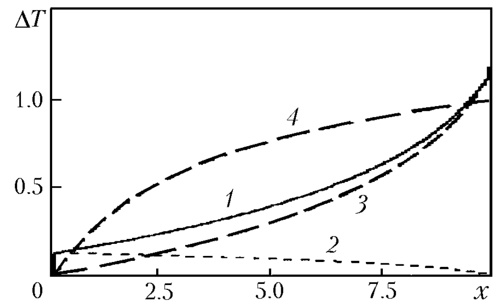


Fig. 3. Contribution of the effect of reverse influence along the length of the porous rod at the time the displacement is terminated, $t = \tau$: 1) overall temperature; 2) contribution of the barothermal effect on water; 3) absolute contribution of the effect of reverse influence; 4) relative contribution of the effect of reverse influence.

$$T = \begin{cases} \varepsilon_1 \dfrac{P_0}{L} x\,, \quad x \le \dfrac{c_1}{c_{\text{m}1}} \dfrac{k}{\mu_1} \dfrac{P_0}{L} (t-\tau)\,; \\ \varepsilon_1 \dfrac{c_1}{c_{\text{m}1}} \dfrac{k}{\mu_1} \dfrac{P_0^2}{L^2} (t-\tau) + T_1 \left(x - \dfrac{c_1}{c_{\text{m}1}} \dfrac{k}{\mu_1} \dfrac{P_0}{L} (t-\tau)\,,\ \tau \right), \quad \dfrac{c_1}{c_{\text{m}1}} \dfrac{k}{\mu_1} \dfrac{P_0}{L} (t-\tau) \le x \le L\,. \end{cases} \tag{25}$$

Having substituted the corresponding expression for T_1 from (23) into (25), we obtain

$$T = \begin{cases} \varepsilon_1 \dfrac{P_0}{L} x\,, \quad x \le \dfrac{c_1}{c_{\text{m}1}} \dfrac{k}{\mu_1} \dfrac{P_0}{L} (t-\tau)\,; \\ \varepsilon_1 \dfrac{c_1}{c_{\text{m}1}} \dfrac{\mu_1}{\Delta\mu} m P_0 \ln \left(1 + \dfrac{c_{\text{m}1}}{c_1 m} \dfrac{\Delta\mu}{\mu_1 L} \left[x - \dfrac{c_1}{c_{\text{m}1}} \dfrac{k}{\mu_1} \dfrac{P_0}{L} (t-\tau) \right] \right) + \varepsilon_1 \dfrac{c_1}{c_{\text{m}1}} \dfrac{k}{\mu_1} \dfrac{P_0^2}{L^2} (t-\tau)\,, \\ \dfrac{c_1}{c_{\text{m}1}} \dfrac{k}{\mu_1} \dfrac{P_0}{L} (t-\tau) < x < \dfrac{c_1}{c_{\text{m}1}} mL + \dfrac{c_1}{c_{\text{m}1}} \dfrac{k}{\mu_1} \dfrac{P_0}{L} (t-\tau)\,; \\ \varepsilon_1 \dfrac{c_1}{c_{\text{m}1}} \dfrac{\mu_1}{\Delta\mu} m P_0 \ln \left\{ \dfrac{c_{\text{m}1}}{c_{\text{m}1} - c_1 m} \left[\dfrac{\mu_2}{\mu_1} - \dfrac{\Delta\mu}{L\mu_1} \left[x - \dfrac{c_1}{c_{\text{m}1}} \dfrac{k}{\mu_1} \dfrac{P_0}{L} (t-\tau) \right] - \dfrac{c_1}{c_{\text{m}1}} m \right] \right\} - \\ - \varepsilon_2 \dfrac{c_2}{c_{\text{m}2}} \dfrac{\mu_2}{\Delta\mu} m P_0 \ln \left\{ \dfrac{c_{n1}}{c_{\text{m}1} - c_1 m} \left[1 - \dfrac{\Delta\mu}{L\mu_2} \left(x - \dfrac{c_1}{c_{\text{m}1}} \dfrac{k}{\mu_1} \dfrac{P_0}{L} (t-\tau) \right) - m \dfrac{c_1}{c_{\text{m}1}} \dfrac{\mu_1}{\mu_2} \right] \right\}, \\ \dfrac{c_1}{c_{\text{m}1}} mL + \dfrac{c_1}{c_{\text{m}1}} \dfrac{k}{\mu_1} \dfrac{P_0}{L} (t-\tau) < x < L\,. \end{cases} \tag{26}$$

On termination of the stage indicated, a steady-state temperature distribution is set:

$$T = \varepsilon_1 \frac{P_0}{L} x\,, \quad 0 < x < L\,, \quad t > \tau + \frac{c_{\text{m}1}}{c_1} \frac{\mu_2}{k} \frac{L^2}{P_0}\,. \tag{27}$$

Expressions (17) and (22) for the water-saturated zone and (13) for the oil-saturated one, as well as Eqs. (26) and (27), entirely solve the problem set. Below we consider the results of the calculations performed on the basis of the expressions obtained.

Figure 1 presents the dependences of the magnitude of the barothermal effect ΔT on time in water–oil displacement in a porous thermally insulated rod of length $L = 10$ m at different points of this rod. In the calculations, the following values of the physical parameters were adopted: the Joule–Thompson coefficients for water $\varepsilon_1 = 0.02$

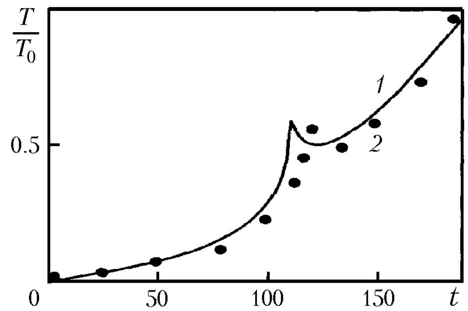


Fig. 4. Comparison between the calculated and experimental values of the barothermal effect: 1) calculated curve of relative temperature; 2) experimental points.

K/atm, for oil ε_2 = 0.04 K/atm; water viscosity $\mu_1 = 10^{-3}$ Pa·sec, oil viscosity $\mu_2 = 10^{-2}$ Pa·sec, difference of pressures at the rod ends P_0 = 100 atm; volumetric heat capacities of water c_1 = 1000 kcal/(K·m^3), of oil c_2 = 400 kcal/(K·m^3), of the water-saturated porous medium c_{m1} = 820 kcal/(K·m^3), of the oil-saturated one c_{m2} = 700 kcal/(K·m^3); the porous medium permeability $k = 10^{-11}$ m^2, and the porosity m = 0.2.

All the curves have similar characteristic features of their behavior, which are as follows. For short times an increase in the temperature which attains a maximum on approach of the water front is observed. This maximum increases with the coordinate x. On attainment of the highest value, a decrease in the temperature begins, which is explained by the characteristic features of the distribution of temperature in the region of the reverse influence of the oil-saturated zone on the water-saturated one. Thereafter, the temperature on all the curves attains a minimum, and then it begins to grow. The increase in the temperature continues till a steady-state value is established at each point.

Figure 2 presents the dependences of the value of the barothermal effect on the coordinate x for different times. For $t < \tau$, at high values of x the plots contain portions over which the temperature is independent of x (curves 1 and 2). These portions correspond to the oil-saturated zone of the porous medium. Curve 3 shows the temperature distribution at the moment when water reaches the right-hand side of the porous rod. Precisely for this curve is the contribution of the reverse thermal effect observed within the range 2.4 m $< x <$ 10 m. For the times $t > \tau$, curves 4–8 reflect the process of the "carrying-out of residual heating" and development of a steady-state distribution of temperature. The indicated curves contain portions of a steady-state temperature at low values of x and portions with an unsteady-state temperature at high values of x. From the analysis of the curves, it follows that the process of establishment of the temperature at the above-indicated values of the parameters occupies a time interval of 0.7τ.

Figure 3 depicts the contribution of the effect of the reverse influence on temperature distribution at the moment of termination of the displacement. Curve 1 represents the dependence of temperature on the coordinate x; this dependence is determined by the contributions of the barothermal effect in water (curve 2) and of the effect of reverse influence of the displaced fluid (curve 3). From a comparison of the curves, it follows that the main contribution to the temperature field is made by the effect of reverse influence. This conclusion is illustrated more vividly by curve 4, which represents the relative contribution of the effect of reverse influence, i.e., the ratio of the absolute magnitude of the effect of reverse influence to the overall temperature. The results of comparison of the calculated and experimental curves obtained on a porous-medium model of length 1 m on 10-atm depression are indicative of their satisfactory agreement (Fig. 4).

Thus, in the zone of reverse effect, the temperature field of a filtered water is mainly determined by the influence of the oil displaced. The temperature effect of the heating of water increases appreciably in this case.

CONCLUSIONS

1. On displacement of oil of elevated viscosity by water, a transition zone is formed due to the mutual influence of oil and water; in this zone, the barothermal effect of water is increased repeatedly. The zone of the mutual influence of water and oil (the zone of reverse thermal influence of the fluid displaced) has great dimensions, and by the time of termination of displacement process it occupies more than 70% of the displacement-zone length. In the

zone of the reverse influence, the temperature field of the filtered water is mainly determined by the influence of the oil displaced.

2. The process of establishment of the temperature field consists of two stages: a) the process of a change in the temperature occurs in a variable pressure field attributable to the motion of the displacement boundary; b) the establishment of temperature occurs due to thermodynamic effects in water and to the carrying-out of the residual porous-medium heating formed by the end of the first stage.

3. The dependence of temperature on time at each point of the displacement zone is nonmonotonic. The temperature attains a maximum at the time of approaching the water front; then it passes through a minimum and again increases to a steady-state value. The attainment of the temperature maximum is explained by the increase in the effective pressure drop overcome by oil and occurring because of the multiple difference between the viscosities of water and oil.

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NOTATION

C and C_1, integration constants; c_1 and c_2, volumetric heat capacities of water and oil, respectively, J/(K·m^3); c_{m1} and c_{m2}, volumetric heat capacities of water- and oil-saturated porous media, J/(K·m^3); k, permeability of a porous medium, m^2; L, length of a porous rod, m; m, porosity; P and P_0, pressure and difference of pressures at the ends of the rod, Pa; $R(t)$ and $R_1(t)$, functions that describe the position of the displacement-front boundary and of the left boundary of the intermediate zone, m; s_j, the value of the water-saturability jump at the boundary of the displacement zone; T, magnitude of the barothermal effect, K; t, current time, sec; U, velocity of convective heat transfer, m/sec; x, coordinate, m; β, compressibility factor, Pa^{-1}; ε_1 and ε_2, Joule–Thompson coefficients for water and oil, K/Pa; μ, relative viscosity of oil; μ_1 and μ_2, viscosities of water and oil, Pa·sec; τ, time of water–oil displacement from the porous rod, sec; χ, coefficients of piezoconductivity, m^2/sec. Subscripts: m, porous medium; j, jump; i, number of the region.

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