Journal of Applied Mechanics and Technical Physics, Vol. 40, No. 3, 1999

BAROTHERMIC EFFECT IN FILTRATION OF ANOMALOUS OIL AND WATER

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UDC 532.546

The regularities of formation of the temperature field at the exit from a pool are established from a numerical study of the temperature field due to the barothermic effect in filtration of anomalous oil and water. It is shown that the anomalous properties of oil enhance the contribution of adiabatic cooling at the initial stages of production from an oil well. In simultaneous motion of anomalous oil and water, a nonmonotonic dependence of the fluid temperature on the saturation of the pool with water is observed.

As is known, the study of the temperature fields due to the barothermic effect is of practical significance. At present, the temperature fields due to the Joule–Thomson effect and adiabatic effect in the filtration of a Newtonian fluid have been primarily studied [1–3].

The barothermic effect in the filtration of anomalous fluids have been inadequately studied. Filippov and Khusainova [4] reported an approximate analytical solution for the problem of the temperature field of the barothermic effect in the filtration of viscoplastic oil.

The present paper deals with a numerical study of the temperature field due to the Joule–Thomson effect and the adiabatic effect in the filtration of anomalous oil and water. The mathematical model for the nonisothermal filtration of anomalous oil and water ignores the diffusion transfer of mass and heat, the mutual dissolution of oil and water, heat exchange with the ambient medium, and gravity and capillary forces.

1. The mathematical model is based on the equation of conservation of mass for the phases, the equation of motion, and the heat inflow equation.

With allowance for the above remarks, the equation of conservation of mass for the phases in the plane-radial case has the form

$$\frac{\partial m\rho_i S_i}{\partial t} + \frac{1}{r}\frac{\partial r m\rho_i S_i V_i}{\partial r} = 0, \qquad i = 1, 2. \tag{1}$$

The values 0, 1, and 2 of the subscript i refer to rock, water, and oil, respectively, S_i and V_i are the saturation and velocity of motion of the ith phase, ρ_i is the gravity of the ith phase, and m is the porosity.

The equation of motion for water is written in the form of the Darcy filtration law:

$$mS_1V_1 = -\frac{Kk_1}{\mu_1}\frac{\partial P}{\partial r}. \tag{2}$$

For the oil phase, we use the law of filtration of a viscoplastic fluid [5]:

$$mS_iV_i = -\frac{Kk_i}{\mu_i}\Big(\frac{\partial P}{\partial r} - G\Big) \quad \text{for} \quad \frac{\partial P}{\partial r} > G, \qquad mS_iV_i = 0 \quad \text{for} \quad \frac{\partial P}{\partial r} < G. \tag{3}$$

Here K is the absolute permeability, k_i is the permeability of the phase, μ_i is the viscosity of the ith phase, P is the pressure, and G is the initial shear pressure gradient.

Bashkir State University, Ufa 450000. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 40, No. 3, pp. 18–21, May–June, 1999. Original article submitted October 14, 1997; revision submitted June 17, 1998.

The heat inflow equation in the approximation of a one-temperature model that takes into account the Joule–Thomson effect, the adiabatic effect, and convective heat transfer and ignores thermal conductivity has the form [1, 6]

$$\frac{\partial}{\partial t}\left[(1-m)\rho_0 C_0 T + \sum_{i=1}^{2} m\rho_i C_i S_i T\right] + \frac{1}{r}\frac{\partial}{\partial r} r\left[m\sum_{i=1}^{2}\rho_i C_i S_i V_i T\right]$$
$$+m\sum_{i=1}^{2}\rho_i C_i S_i V_i \varepsilon_i \frac{\partial P}{\partial r} - m\sum_{i=1}^{2}\rho_i C_i S_i \eta_i \frac{\partial P}{\partial t} = 0. \qquad (4)$$

Here the following thermodynamic parameters are introduced: T is the temperature, C_i is the heat capacity, ε_i is the Joule–Thomson coefficient, and η_i is the adiabatic coefficient of the ith phase.

The first term of Eq. (4) represents the change in the heat content of the system, the second term represents convective heat transfer, and the third and fourth terms are the contributions of the Joule–Thomson and adiabatic effects, respectively.

The initial and boundary conditions are

$$\begin{aligned} &t = 0,\ r > 0: && S_i = S_{i0}, && P = P_0, && T = T_0,\\ &t > 0,\ r = R_0: && P = P_K(t), && P_K^0 \leqslant P_K(t) \leqslant P_0, &&\\ &t > 0,\ r = R: && P = P_0, && S_i = S_i^0, && T = T_0. \end{aligned} \qquad (5)$$

The phase permeabilities were specified in the same manner as in [7]. The oil and water densities are functions of pressure and temperature.

System (1)–(4) with initial and boundary conditions (5) was solved numerically using a conservative finite-difference scheme of through calculation. The saturations of the phases and the temperature were calculated by an explicit scheme, and the pressure was calculated by an implicit scheme. Testing was performed using the known analytical solutions of the temperature field due to the Joule–Thomson effect for the filtration of Newtonian oil [1].

2. The calculations were performed for the following model values of the thermohydrodynamic parameters of the phases, which are close to the real rock values [1, 8]:

$$C_0 = 800\ \text{J/(kg}\cdot\text{K)},\qquad C_1 = 4000\ \text{J/(kg}\cdot\text{K)},\qquad C_2 = 2000\ \text{J/(kg}\cdot\text{K)},$$
$$\varepsilon_1 = 0.2\ \text{K/MPa},\qquad \varepsilon_2 = 0.4\ \text{K/MPa},\qquad \eta_1 = 0.015\ \text{K/MPa},\qquad \eta_2 = 0.13\ \text{K/MPa}.$$

The initial rock pressure P_0 and the minimum pressure P_K^0 at the rock boundary ($r = R_0$) are equal to 20.0 and 14.0 MPa, respectively.

The calculations were performed for the following initial shear pressure gradients [9]: $G = 0$, 0.02, and 0.05 MPa/m. The water and oil viscosities were assumed to be $\mu_1 = 0.1$ mPa · sec and $\mu_2 = 0.4$ mPa · sec, respectively. The initial water saturation was varied within $S_0 = 0$, 0.25, 0.5, and 0.7.

3. Figure 1 shows results of calculation of the temperature field for filtration of anomalous oil with various initial shear pressure gradients. Here curve 1 refers to $G = 0$, curve 2 to $G = 0.2$ MPa/m, and curve 3 to $G = 0.5$ MPa/m. For $G = 0$, the time dependence of temperature is similar to the solution of the problem of the temperature field due to the barothermic effect in the filtration of Newtonian oil [1]. Figure 1 compares the experimental dependence of temperature obtained in survey of well No. 6558 (Bashkiria) (curve 5) with the calculated dependence (curve 4) for $K/\mu_2 = 0.35$.

The curve of temperature versus time shows the characteristics portions associated with the development of the adiabatic effect and the Joule–Thomson effect. In the early stages of production from a well (drop of pressure at the exit from the pool), adiabatic cooling of the oil is observed. Further, because of the predominance of throttling heating over adiabatic cooling, the temperature increases and a positive stationary temperature is established. In filtration of anomalous oil, the formation of the thermal field at the exit from the pool is similar to the case of filtration of Newtonian oil. However, with increase in the initial pressure gradient, the contribution of adiabatic cooling increases (curves 2 and 3 in Fig. 1), and the

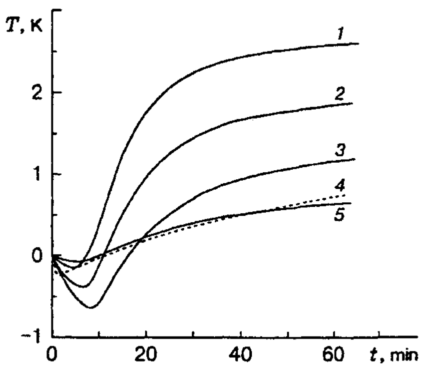

Fig. 1. Temperature versus time for various initial shear pressure gradients: curve 1 refer to $G = 0$, curve 2 to $G = 0.2$ MPa/m, curve 3 to $G = 0.5$ MPa/m, curve 4 to $G = 0$ and $K/\mu_2 = 0.35$, and curve 5 are the results of survey of well No. 6558 (Bashkiria).

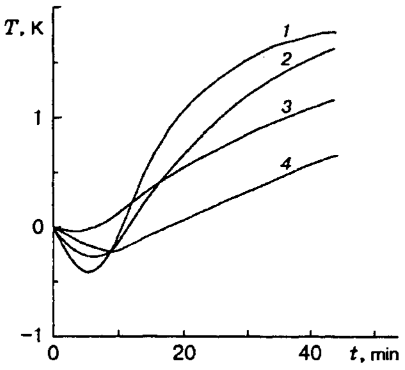

Fig. 2

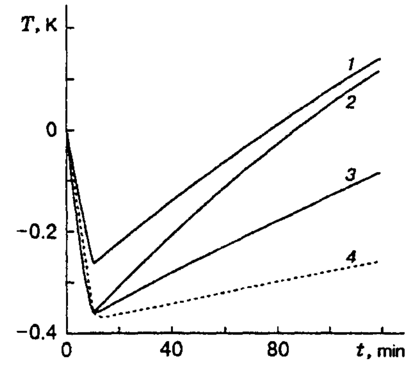

Fig. 3

Fig. 2. Time dependence of temperature for various initial water saturations ($G = 0.2$ MPa/m): curve 1 refers to $S = 0$, curve 2 to $S = 0.25$, curve 3 to $S = 0.7$, and curve 4 to $S = 0.5$.

Fig. 3. Time dependence of temperature for various viscosities of oil ($G = 0.02$ MPa/m): curve 1 refers to $\mu_2 = 4$ mPa · sec (ignoring initial shear gradient), curve 2 refers to $\mu_2 = 2$ mPa · sec, curve 3 to $\mu_2 = 4$ mPa · sec, and curve 4 to $\mu_2 = 10$ mPa · sec.

minimum of the temperature is shifted toward larger times. In this case, the magnitude of the stationary positive anomaly decreases.

Figure 2 shows the time dependences of temperature at the exit from the pool for various saturations of the pool with water (water content) for an initial pressure gradient $G = 0.2$ MPa/m. It can be seen that the dependence of temperature at the exit from the pool on the saturation of the pool with water is nonmonotonic. With increase in the saturation of the pool with water (curves 1, 2, and 4 in Fig. 2), the magnitudes of adiabatic cooling and throttling heating decreases, and the minimum of temperature is shifted toward larger times. With further increase in the saturation of the pool with water, in particular, for $S = 0.7$ (curve 3 in Fig. 2), more intense throttling heating of the fluid at the exit from the pool is observed.

Figure 3 gives features of the temperature field in the filtration of anomalous oil with various viscosities. It can be seen that an increase in the oil viscosity (decrease in mobility) increases the duration of the adiabatic cooling compared to throttling heating of the oil.

Thus, on the one hand, the anomalous properties of the fluids on the temperature field due to the barothermic effect enhance the contribution of adiabatic cooling up to the development of the phase of motion of the anomalous fluid at initial times of production from a well, and, on the other hand, they decrease throttling heating of the anomalous oil. For joint motion of the anomalous oil and water, a nonmonotonic dependence of the temperature field on the saturation of the pool with water is observed. Initially, as the saturation of the pool with water increases, the positive temperature anomaly decreases, and with further increase in the water content of the pool, it increases. The results obtained can be used to interpret data of thermal studies on pools with anomalous properties of oil.

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