THERMAL FIELD OF AN OIL BED IN A NONSTATIONARY PRESSURE FIELD

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UDC 532.546

We carried out a numerical investigation of the temperature field arising in an oil bed due to the Joule–Thomson effect and the heat of deaeration of the liquid in the nonstationary pressure field in displacement of oil by water. The formation of the temperature field depends substantially on the initial flooding of the bed and the approach of the front of the displacement of oil by water. The value of the water-oil ratio exerts an effect on the sign of the temperature anomaly at the outlet from the bed.

The processes of start-up and shut-down of a well and compressor exploitation of oil wells and beds are characterized by a nonstationary pressure field. In these processes the temperature field of the bed owes its origin to manifestation of a barothermal effect [1, 2] and, when the pressure decreases below the saturation pressure, to the heat of deaeration of the liquid [3]. Below we carry out a numerical investigation of the temperature field that arises in a bed due to the Joule–Thomson effect and the heat of deaeration of the liquid in the nonstationary pressure field in displacement of oil by water. A decrease in the pressure in the well below the saturation pressure leads to deaeration of the oil and formation of a gas phase in the bed. Therefore in approach of the front of displacement of oil by water a three-phase filtrational flow is observed in the region of deaeration in the bed. The mathematical model of the process does not take into account diffusive transfer of the components of the mixture, longitudinal transfer of heat by conduction, the adiabatic effect, mutual dissolution of oil and water, or the change in the constituent composition of the oil being deaerated.

The mathematical model for calculation of the temperature field of a bed in three-phase filtration in a nonstationary pressure field with account for the Joule–Thomson effect and liquid deaeration of the liquid is based on the mass conservation equations of the phases and the components, heat input equations, and equations of motion in the form of the Darcy law.

With the above assumptions, in the plane-parallel case we have the following system of equations:

$$\frac{\partial m \rho_i S_i}{\partial t} + \frac{1}{r} \frac{\partial r m \rho_i S_i V_i}{\partial r} = I_{(ij)} , \quad i = 1, 2, 3 ; \tag{1}$$

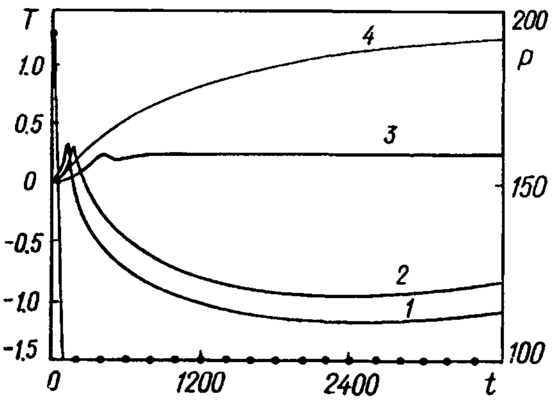
$$\frac{\partial m \rho_i C_{ik} S_i}{\partial t} + \frac{1}{r} \frac{\partial r m \rho_i C_{ik} S_i V_i}{\partial r} = I_{(ij)k} , \quad i = 1, 2, 3 ; \quad k = 1, 2, 3 ; \tag{2}$$

$$m S_i V_i = - \frac{K k_i}{\mu_i} \frac{\partial P}{\partial r} , \quad i = 1, 2, 3 ; \tag{3}$$

$$\frac{\partial}{\partial t} \left[(1 - m) \rho_0 c_0 T + \sum_{i=1}^{3} m \rho_i c_i S_i T + m \rho_i S_i L \right] +$$
$$+ \frac{1}{r} \frac{\partial}{\partial r} r \left[m \sum_{i=1}^{3} \rho_i c_i S_i T + m \rho_1 S_1 V_1 L \right] + m \sum_{i=1}^{3} \rho_i c_i S_i V_i \varepsilon_i + \frac{\partial P}{\partial r} = 0 ; \tag{4}$$

Bashkir State University, Ufa. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 72, No. 2, pp. 271-274, March-April, 1999. Original article submitted August 20, 1997.

 1062-0125/99/7202-0250$22.00 ©1999 Kluwer Academic/Plenum Publishers



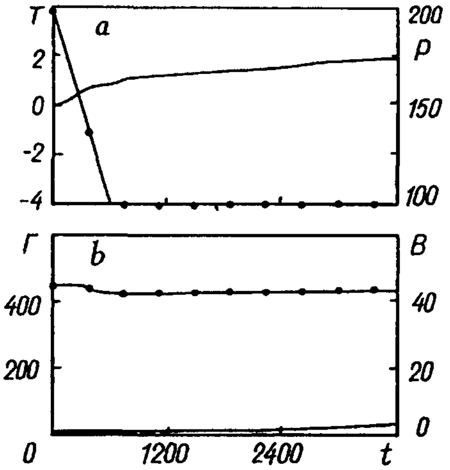


Fig. 1. Temperature (curves 1-4) at the outlet from the bed versus time with a change in the pressure (the curve with dots) at the bottom of the well and a pressure of saturation of oil with gas P_s = 15 MPa: 1) initial flooding $S = 0$, 2) 25%, 3) 50, 4) 75. T, °C; P, MPa; t, sec.

Fig. 2. Temperature (the curve), pressure (the curve with dots) (a), water-oil ratio (the curve), gas factor (the curve with dots) (b) versus time with displacement of oil from the flooded bed (S = 50%) and a pressure of saturation of oil with gas P_s = 15 MPa. B, Γ, m^3/m^3.

$$\sum_{i=1}^{3} S_i = 1 , \quad \sum_{k=1}^{3} C_{ik} = 1 . \tag{5}$$

The Joule–Thomson coefficient ε_i is calculated from the formula

$$\varepsilon_i = 1/\rho_i c_i .$$

The initial and boundary conditions are

$$t = 0 , \quad r > 0: \quad S_i = S_{i0} , \quad C_{ik} = C_{ik}^0 , \quad P = P_0 , \quad T = T_0 ;$$

$$t > 0 , \quad r = R_0: \quad P = P_f(t) ; \quad P_f^0 \leq P_f(t) \leq P_0 ;$$

$$t > 0 , \quad r = R: \quad P = P_0 , \quad S_i = S_i^0 ; \quad T = T_0 . \tag{6}$$

The solubility of the gases obeys Henry's law, and the mass concentrations are calculated from the formula

$$C_{i1} = (1 + \alpha P/\rho_1 \beta)^{-1}$$

using literature data on the Henry coefficients α and the coefficient of volumetric expansion of oil β [4]. Phase permeabilities were specified in the form given in [5]. The densities of the oil, water, and gas are functions of the pressure. The intensities of mass transfer in deaeration are taken in the form

$$I_{(ij)k} = b_{(ij)k} (P_s - P) .$$

The system of equations (1)-(6) was solved numerically on the basis of a conservative finite-difference scheme of continuous calculation. The saturation of the phases and the temperature were calculated by an explicit scheme, and the pressure was calculated by an implicit scheme. Here, at the first stage of the calculations we determine the saturation of the phases and the pressure, and at the second stage the distribution of the temperature.

We carried out multivariant calculations of the temperature field for values of the thermodynamic parameters of the phases within the following limits: c_1 = 2000–4000 J/(kg·K), c_2 = 3000–5000 J/(kg·K), c_3 = 1600–2400 J/(kg·K), ε_1 = –(2–4) K/MPa, ε_2 = 0.1–0.3 K/MPa, ε_3 = 0.16–0.56 K/MPa, L = 50–200 kJ/kg. The initial pressure in the bed P_0 and the minimum final pressure P_f^0 on the boundary of the bed ($r = R_0$) were varied in the ranges P_0 = 16.0–20.0 MPa, P_f^0 = 9.0–14.0 MPa.

Figures 1 and 2 show dependences for the following values of the thermodynamic parameters of the phases: c_0 = 800 J/(kg·K), c_1 = 3000 J/(kg·K), c_2 = 4000 J/(kg·K), c_3 = 2000 J/(kg·K). The heat of the phase transition in deaeration of oil was evaluated on the basis of the data from [6] and was taken equal to L = 100 kJ/kg. The viscosities of the gas, aerated water, and oil phases were taken to be, respectivelly: μ_1 = 0.01 MPa·sec, μ_2 = 0.2 MPa·sec, μ_3 = 0.4 MPa·sec.

Experimental investigations of the temperature field in a well at pressures below the saturation pressure show that the formation of the temperature field is greatly influenced by the thermal effects caused by deaeration of the liquid [7]. Here, it is of interest to study, by means of a numerical experiment, the effect of flooding of beds on the temperature field under conditions of deaeration of the liquid. Below we present the most typical cases of formation of a temperature field at different degrees of flooding of the bed (curves 1-4, Fig. 1) and the pressure P (the curve with dots) at the outlet from the bed as a function of time. At a water content of the bed below 50% (curves 1 and 2) throttling heating of the liquid is observed after the decrease in the pressure. When the pressure falls below the saturation pressure, deaeration and, as a result, a decrease in the temperature due to the heat of deaeration and throttling of the gas occur. An increase in the water content of the bed (in the water-oil ratio) leads to an increase in the flow temperature, and a positive temperature anomaly (curves 3 and 4) is observed at a water content of the bed of 50% or more. The results obtained correspond to a gas factor (the ratio of the volumetric discharge of gas to the volumetric discharge of liquid from the bed under normal conditions) equal to 450 m^3/m^3.

Thus, depending on the value of the water-oil ratio, both positive and negative temperature anomalies can be observed in a bed upon a decrease in the pressure below the saturation pressure. The minimum water-oil ratio at which a change in the sign of the temperature anomaly occurs is called the inverse water-oil ratio. It depends on many factors and, as multivariant calculations show, it depends primarily on the heat of deaeration of the oil, the Joule–Thomson coefficient of the gas and the liquids, and the gas factor. Therefore, in each specific case these values can be calculated from available data on the thermodynamic parameters of the bed system. In the present case, at water-oil ratios higher than 5 m^3/m^3, which corresponds to a 50% water content of the bed, a positive temperature anomaly will be observed.

Since most oil deposits enter a late stage of exploitation, one can observe an inrush of the front of injected water in wells. Below we present results of a calculation of the temperature field under conditions of flooding of wells by injected water.

Curves of the change in the temperature, pressure, and gas factor for a partially flooded bed (50%) are presented in Fig. 2. We see that at the initial stage, after putting the well into operation, the gas factor decreases somewhat and then it stabilizes. The temperature effects are smoothed in this case due to the smaller fraction of gas in the flow. Moreover, at a 50% water content a positive temperature anomaly is observed. Thereafter, there are no jumps or oscillations of the gas factor or the temperature in connection with the motion of the displacement front.

Thus, the temperature distribution in a bed in a nonstationary pressure field in the presence of deaerated liquid depends substantially on the initial flooding of the bed and the approach of the front of displacement of oil by water to the outlet from the bed. Here there is an inverse value of the water-oil ratio at which transition from a positive to a negative temperature anomaly occurs. The value of the inverse water-oil ratio depends on the specific geological-physical and thermodynamic parameters of the bed and the fluid, and therefore in each specific case it must be calculated separately. The results obtained can be used to interpret the data of thermal investigations of wells.

NOTATION

S_i and V_i, saturation and speed of the i-th phase; C_{ik}, concentration of the k-th component in the i-th phase; ρ_i, density of the i-th phase; K, absolute permeability; k_i, phase permeability; m, porosity; P, pressure; T, temperature; c_i, heat capacity; S_{i0}, initial saturation of the bed by the i-th phase; C_{ik}^0, initial concentration of the k-th component in the i-th phase; P_0, initial bed pressure; P_f^0, final pressure in the well; P_s, saturation pressure; $b_{(ij)k}$, proportionality factor; T_0, initial temperature; Γ, gas factor; B, water-oil ratio. Subscripts: i and k, different phases and components of the mixture; 0, rock; 1, gas; 2, water; 3, oil.

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