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# SPECIAL FEATURES OF HEAT AND MASS EXCHANGE IN THE FACE ZONE OF BOREHOLES UPON INJECTION OF A SOLVENT WITH A SIMULTANEOUS ELECTROMAGNETIC EFFECT

**F. L. Sayakhov, L. A. Kovaleva, and N. M. Nasyrov**

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*We consider some unique features specific to the technological process of injection of a solvent into a hydrocarbon deposit with the simultaneous effect of a high-frequency electromagnetic field. We carry out estimates of the losses of the electromagnetic field energy released in the borehole and spent for heating the solvent. It is shown that the presence of volumetric heat sources in the face zone of the borehole due to the field effect leads to intense and deep heating of the productive bed with a small temperature gradient.*

**Introduction.** In recent years many branches of industry have made ever-increasing use of technologies based on exposure of a working medium to the direct effect of electric, magnetic, and electromagnetic fields, including the effect of high-frequency (HF) electromagnetic fields (EMF). The importance of such investigations and current interest in them are due to the fact that in the process of interaction with technological working media, an electromagnetic field can convert into other forms of physical fields: temperatures, pressures, thermoelastic stresses, etc. Moreover, an external electromagnetic field influences transfer phenomena, chemical conversions, phase changes, and kinetic processes in disperse systems [1].

In the practice of development of oil deposits an efficient method for intensifying the inflow of not easily extractable high-viscosity oils and bitumens in deposits with complicated physicogeological conditions is technologies based on the effects of high-power external high- and superhigh-frequency electromagnetic fields. The need to develop such deposits is attributable to the fact that fuel-electric power and raw material-extractive industries, which are being intensively developed, require utilization of alternative sources of hydrocarbon raw material such as high-viscosity and bitumen oils not extractable from a bed by standard techniques. Their reserves considerably exceed those of ordinary oils.

The existing techniques for production of high-viscosity hydrocarbons are of limited efficiency because of the low acceleration capacity of bed collectors and the low thermal conductivity of rocks. This hinders the production of oil by mixed displacement by solvent or pumping a hot heat carrier and heating the bed by a face heater. New technologies are needed that would combine the advantages of the mixed displacement of fluid and heating of the medium. This may well be a technology that combines the effects of a high-frequency electromagnetic field and a solvent on the bed. Moreover, electromagnetic waves (EMW) from a ground-based generator are transmitted into the bed by means of a coaxial system of pipes of the borehole, while the solvent is passed through the inner pipe of the same system. Due to the finite electrical conductivity of the pipes, they are heated and the solvent is heated together with them. Thus, when the solvent enters the bed, it is hot, with its temperature being dependent on the pressure at the face of the borehole, the power and frequency of the EMW generator, and many other factors, i.e., it is possible to control the depth and intensity of the effect exerted on the bed [2].

The problems of simultaneous isothermal motion of several mutually soluble fluids were treated in [3]. The problem of nonisothermal filtration with pumping of a hot solvent is considered in [4], where a self-similar solution of it was obtained.

Below we investigate the process of pumping a hot solvent with the simultaneous effect of a high-frequency electromagnetic field on the bed. We consider the case of radial filtration.

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**1. Statement of the Problem and Basic Equations.** It is assumed that the distances over which the parameters of the medium change significantly considerably exceed the characteristic dimensions of the pores and the spaces between them, while the latter greatly exceed the molecular-kinetic dimensions (the molecular mean free paths). The temperatures of the phases and components in each elementary volume of the porous medium are identical. There are no deformations of the skeleton of the porous medium. The motion of the fluid in the porous medium is inertialess and obeys Darcy's law.

The general system of equations that describes the process includes a continuity equation for the entire mixture, Darcy's filtration law, and equations of heat addition and continuity for the components. With allowance for the real differences in pressure in beds, the continuity equation is transformed into an equation of piezoconductivity [5], and ultimately the distributions of pressure, temperature, and concentration of the components are determined by a system of equations involving equations of piezoconductivity, thermal conductivity, and convective diffusion:

$$\frac{\partial P}{\partial t} = \frac{k}{m\beta_s + \beta_{sk}} \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{r}{\mu_s} \frac{\partial P}{\partial r} \right); \quad (1.1)$$

$$\frac{\partial T}{\partial t} = \kappa_{bed} \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) - \frac{v \rho_s c_s}{\alpha_{bed}} \frac{\partial T}{\partial r} + \frac{Q}{\alpha_{bed}}; \quad (1.2)$$

$$m \frac{\partial C_j}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( Dr \frac{\partial C_j}{\partial r} \right) - v \frac{\partial C_j}{\partial r}; \quad (1.3)$$

$$v = -\frac{k}{\mu_s} \frac{\partial P}{\partial r}; \quad D = \delta (D_0 + \lambda v). \quad (1.4)$$

Here $j = 1, 2$ are the indices for the solvent and the oil, respectively; $D_0 << \lambda v$; in the absence of a field $\delta = 1$; $\mu_s$ is determined from Kendall's formula

$$\ln \mu_s = C_1 \ln \mu_1 + C_2 \ln \mu_2 .$$

In turn, the viscosity of the components depends on the temperature and is determined from the expression

$$\mu_j = \mu_{0j} \exp (-\gamma_j \Delta T) ,$$

where $\Delta T = T - T_0$.

The obvious relation $C_1 + C_2 = 1$ is satisfied, the therefore the solution is sought relative to $C_1$.

The expression for distributed heat sources can be written in the form [6]

$$Q = 2\alpha J \frac{r_0}{r} \exp [-2\alpha (r - r_0)] , \quad J = \frac{N_0}{S_b}; \quad S_b = 2\pi r_0 h ,$$

where $J$ is determined by the power $N_0$ and the radiator surface area $S_b$; $r_0$ is the radius of the radiator of electromagnetic waves (the radius of the borehole).

**2. Energy Losses in the Transmission Line for Electromagnetic Waves and Justification of Boundary Conditions.** A coaxial system of inner and outer pipes of the borehole is usually used as the line for transmitting the energy of electromagnetic waves from the mouth of the borehole to the face: tubing string (TS) and casing string. While propagating in the borehole clearance as in a coaxial transmission line, electromagnetic waves inevitably lose a portion of their energy because of the finite electrical conductivity of the pipes and dielectric losses in the medium that fills the space between the pipes. But these energy losses can be used to restore boreholes and portions of pipelines clogged by hydrate and paraffin locks and to heat the solvent pumped into the bed.

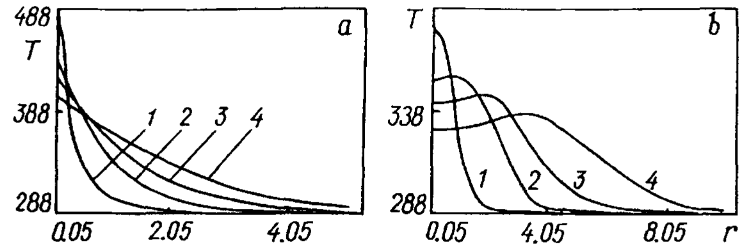

Fig. 1. Temperature distribution at different instants of time: a) $N_0 = 20$ kW, $P_b = 11$ MPa; b) 60 and 15; 1) $t = 2$ days; 2) 10; 3) 20; 4) 40. $T$, K; $r$, m.

In estimating the degree of heating of a solvent in a tubing string as it moves from the mouth of the borehole to the face, we assume that energy losses in the casing string and partially in the tubing string are spent on heating the rocks around the hole, with the remaining portion (20% was assumed in calculations) of the energy released in the tubing string being spent on heating the solvent. In this case, the value of the temperature up to which the solvent is heated is determined from the expression

$$T_b = T_k + \frac{W}{c_k \rho_k g_k}. \tag{2.1}$$

The time rate of the flow of energy $W$ is determined from the formula [7]

$$W = \frac{(N_u - N_0) K_{cas}}{K_{tub} + K_{cas}}.$$

For a known power of the generator of electromagnetic waves, the power of the radiator is determined from the expression

$$N_0 = N_u \exp\left[-2 (K_{tub} + K_{cas}) H\right],$$

The coefficients of attenuation of electromagnetic waves in the tubing string and the casing string are determined as

$$K_{tub} = \frac{R_s}{2Z \ln (R_3/R_2)} \frac{1}{R_2}, \quad R_s^2 = \frac{\pi f \mu_{a.p.}}{\sigma_{tub}}, \quad K_{cas} = \frac{R_s}{2Z \ln (R_3/R_2)} \frac{1}{R_3}, \quad Z^2 = \frac{\mu_0}{\varepsilon_0}.$$

In Eq. (2.1) $g_k$ is determined by the rate of filtration at the face of the borehole:

$$g_k = 2\pi r_0 h v. \tag{2.2}$$

The temperature $T_b$ in Eq. (2.1) is a variable quantity due to the variability of the flow rate $g_k$; it enters into the system of boundary conditions for solution of problem (1.1)-(1.4). The remaining boundary conditions have the form

$$P(r, 0) = P_0; \quad T(r, 0) = T_0; \quad C_1(r, 0) = 0; \tag{2.3}$$

$$P(r_0, t) = P_b; \quad C_1(r_0, t) = 1; \tag{2.4}$$

$$P(r_m, t) = P_0; \quad T(r_m, t) = T_0; \quad C_1(r_m, t) = 0. \tag{2.5}$$

**3. Numerical Solutions and Analysis of Results.** System of equations (1.1)-(1.4) with boundary conditions (2.1)-(2.4) was solved by an implicit finite-difference scheme.

The calculations were performed for the following parameters of the medium: $P_0 = 10$ MPa; $T_0 = T_k = 288$ K; $P_b = 11$ and 15 MPa; $m = 0.3$; $k = 5 \cdot 10^{-13}$ m$^2$; $\kappa_{bed} = 8.91 \cdot 10^{-7}$ m$^2$/sec; $Z = 376.8$ Ω; $f = 13.56$ MHz; $H = 700$

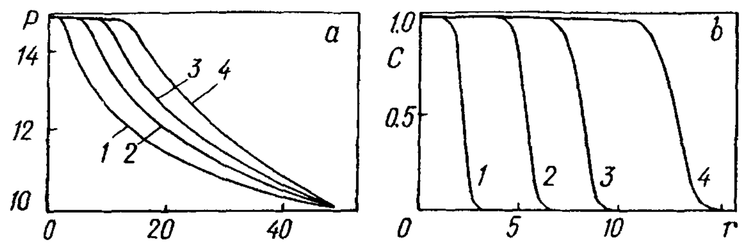


Fig. 2. Distribution of the pressure (a) and the concentration of the solvent (b) at different instants of time ($N_0$ = 60 kW, $P_b$ = 15 MPa): 1) $t$ = 2 days; 2) 10; 3) 20; 4) 40. $P$, MPa.

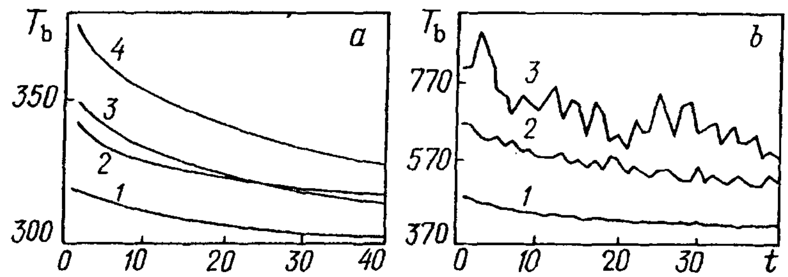


Fig. 3. Dynamics of the change in the temperature at the borehole face in time: a: 1) $N_0$ = 20 kW, $P_b$ = 15 MPa; 2) 20 and 13; 3) 40 and 15; 4) 60 and 15; b) $P_b$ = 11 MPa: 1) $N_0$ = 20 kW; 2) 40; 3) 60. $T_b$, K; $t$, days.

m; $\beta_s = 10^{-9}$ Pa$^{-1}$; $\beta_{sk} = 10^{-10}$ Pa$^{-1}$; $\alpha_{bed}$ = 2,969,000 J/(m$^3$·K); $R_2$ = 0.03015 m; $R_3$ = 0.05015 m; $\mu_{a.p.} = 3.418\cdot 10^{-6}$ H; $\sigma_p = 3.4\cdot 10^6\ \Omega\cdot$m$^{-1}$; $c_k$ = 2057 J/(kg·K); $\rho_k$ = 769 kg/m$^3$; $\rho_s$ = 918 kg/m$^3$; $c_s$ = 2024 J/(kg·K); $\mu_{01} = 1.73\cdot 10^{-3}$ Pa·sec; $\mu_{02}$ = 0.2 Pa·sec; $\gamma_1$ = 0.0128 K$^{-1}$; $\gamma_2$ = 0.042 K$^{-1}$; $h$ = 15 m; $\alpha$ = 0.0198 m$^{-1}$; $r_0$ = 0.05 m; $N_0$ = 20, 40, and 60 kW.

Distributions of temperature in a bed exposed to a high-frequency electromagnetic effect at different instants of time are presented in Fig. 1. As is seen from the figure, the temperature field in the bed depends substantially on both the power of the field and the pressure on the face of the injection borehole. Two characteristic patterns show up in the distribution of temperatures: a monotonic rapid decrease from high values at the borehole face within small distances (Fig. 1a) and deeper heating of the face zone with relatively small values of temperature at the borehole face (Fig. 1b). In this case, in the distribution of temperatures a kink is observed that is characteristic of high-frequency heating, which is due to the action of volumetric heat sources.

Distributions of the pressure and the concentration of the solvent in the bed are shown in Fig. 2. A comparison of the graphs in Figs. 1b and 2b, which illustrate the temperature and concentration fields at the maximum (of those investigated) values of the field power and the solvent injection pressure, shows that mass transfer substantially outstrips heat transfer at corresponding instants of time. However, regulation of these processes in each specific case can be carried out by specifying the corresponding parameters of the effect with allowance for the physical properties of the bed fluid and the agent pumped. Thus, in the case considered, almost the same dynamics of temperature change at the borehole face can be attained by various combinations of the radiator power and the pressure at the borehole face (curves 2 and 3 in Fig. 3a).

Computational investigations showed that at a given constant pressure of solvent pumping the temperature at the borehole face $T_b$ and the closely associated flow rate of the solvent pumped $g_k$ can change nonmonotonically with time, even though the temperature decreases on the whole and the flow rate increases. This is due to the fact that with time an ever larger zone near the borehole exposed to the high-frequency electromagnetic effect is heated, the fluid viscosity in it is decreased, and this favors an increase in the acceleration capacity of the bed, i.e., an increase in the flow rate of the displacing agent. The latter leads, in turn, to a decrease in the temperature at the borehole face and ultimately to possible fluctuations in the temperature and the solvent flow rate (Fig. 3b).

The computational experiments showed that the most important factors that determine the character of the fluctuational process observed are the pressure at the face and the power of the electromagnetic-energy radiator.

It turned out in this case that the maximum amplitude and frequency of the fluctuations of the temperature at the borehole face are characteristic of high powers of the electromagnetic field when small pressure differences are created in the bed (curve 3 in Fig. 3b). An increase in the pressure differences leads to intense heat transfer due to convection, and the temperature "has no time" to undergo substantial changes (Fig. 3a).

The foregoing allows the conclusion that regulation of the solvent injection pressure and the power and frequency of the radiator of electromagnetic waves makes it possible to control the temperature regime of the bed and the processes of heat and mass exchange occurring in it.

## NOTATION

$C_j$, concentration of the mixture components; $c_s$, specific heat of the mixture; $D$, coefficient of convective diffusion; $D_0$, coefficient of molecular diffusion; $f$, frequency of the electromagnetic field; $h$, thickness of the productive bed; $H$, depth of occurrence of the productive bed; $J$, radiation intensity at the borehole face; $k$, permeability of the porous medium; $K_{\text{tub}}$, coefficient of attenuation of electromagnetic waves in the tubing string; $K_{\text{cas}}$, coefficient of attenuation of electromagneting waves in the casing string; $m$, porosity of the medium; $N_0$, power of the radiator of electromagnetic waves; $N_u$, power of the electromagnetic waves at the borehole mouth; $P$, pressure; $P_0$, initial pressure; $P_{\text{b}}$, pressure at the borehole face (boundary); $g_{\text{k}}$, flow rate of the solvent (kerosene) pumped into the bed; $Q$, density of distributed heat sources; $r$, cylindrical coordinate; $r_{\text{m}}$, radius of the bed; $R_2$, outer radius of the TS pipes; $R_3$, inner radius of the pipes of the casing string; $R_s$, active portion of the surface resistance of the pipes; $S_{\text{b}}$, surface area of the radiator of electromagnetic waves; $T$, temperature of the medium; $T_0$, initial temperature; $T_{\text{b}}$, temperature at the borehole face; $T_{\text{k}}$, temperature of the solvent injected; $t$, time; $v$, mean filtration velocity of the fluid; $W$, time rate of flow of the energy lost in the tubing string of the borehole; $Z$, wave resistance of the air filling the hole clearance; $\alpha$, coefficient of attenuation of electromagnetic waves; $\alpha_{\text{bed}}$, volume heat capacity of the bed; $\beta_s$, $\beta_{\text{sk}}$, coefficients of compressibility of the mixture and the rock skeleton; $\gamma_1$, $\gamma_2$, coefficients allowing for the temperature dependence of the viscosity of the solvent and the oil; $\delta$, empirical coefficient whose value depends on the presence and power of the electromagnetic field; $\varepsilon_0$, empirical constant; $\kappa_{\text{bed}}$, thermal diffusivity of the bed; $\lambda$, scattering parameter of the porous medium; $\mu_0$, permeability of vacuum; $\mu_s$, mixture viscosity; $\mu_1$, $\mu_2$, viscosity of the solvent and the oil; $\mu_{01}$, $\mu_{02}$, initial viscosity of the solvent and the oil; $\mu_{\text{a.p.}}$, absolute permeability of the borehole pipes; $\rho_s$, density of the mixture; $\rho_{\text{k}}$, density of the injected solvent; $\sigma_{\text{p}}$, specific electrical conductivity of the borehole pipes. Subscripts: cas, casing; b, boundary; k, kerosene; m, maximum; sk, skeleton; p, pipe; a.p., absolute, pipe; bed, bed.

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