Journal of Engineering Physics and Thermophysics, Vol. 75, No. 1, 2002

HEAT AND MASS TRANSFER IN THE WELL–STRATUM SYSTEM UNDER THE ELECTROMAGNETIC ACTION ON MASSIVE OIL DEPOSITS

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

UDC 532.546:536.421:537.868

The distinctive features of the action of high-frequency electromagnetic radiation on an oil stratum of large thickness are studied. Simultaneously, the oil is sampled, whose viscosity decreases due to the volumetric heating of the oil-saturated porous medium. The loss of heat liberated in the well and the stratum to the surrounding rocks (dry, moistened, and water-saturated ground) is taken into account. The spatial and time distributions of the electromagnetic field strength, the heat sources, and the temperature field are obtained.

Massive thick layers of rocks such as, for example, reef deposits, are distinguished by productive strata of large thickness and by a low permeability of the collector. These deposits include, in particular, the reef depositions of the Ishimbay group of Bashkortostan. However, the high viscosity of oils and (or) choking of the well-bottom zone and of the well itself by solid deposits make it impossible to intensify the production of oil by known methods. We are dealing primarily with thermal methods of action on the well-bottom zone in order to decrease the fluid viscosity and to increase the inflow of oil to the well. In this case, it would be most efficient to perform the heating-up of oil-saturated thick layers by means of high-frequency (HF) and electromagnetic (EM) actions, under which the intense volumetric heating of a medium is accomplished. The energy enters the stratum as a result of propagation of electromagnetic waves in the well and the stratum. Because of the finite electrical conductivity of the tube walls of the well and the presence of dielectric loss in the oil-saturated porous medium the electromagnetic energy is converted into heat energy [1].

Distribution of the Electromagnetic Field Strength and of the Heat Sources in the Stratum. For mathematical description of the high-frequency electromagnetic action on the oil stratum and for calculation of the temperature field one must know the expression for the heat-source density which is determined by the distribution of the electromagnetic field strength. We assume that the high-frequency electromagnetic energy is introduced into the stratum by means of a coaxial system of well tubes, i.e., a pump-compressor tube (PCT) and a casing string. When the stratum is of large thickness, the radiator of electromagnetic waves is a linear antenna of asymmetric excitation; we will call it the asymmetric dipole in contrast to the symmetric dipole described in [2]. As is shown in Fig. 1, the quarter-wave end of the pump-compressor tube, projecting below the casing string (the short arm), and the outer surface of the casing string (the long arm) are the arms of the asymmetric dipole. In Fig. 1, M is the space (observation) point; dz' are the elementary segments on the long and short arms of the dipole; 0 is the excitation point of the dipole; r_1 and r_2 are the distances from the elementary segments on the short and long dipole arms up to the observation point. The upper part of the dipole is so long that the electromagnetic waves propagate along it without reflection, i.e., they are traveling waves.

Bashkir State University, Ufa, Russia; email: Liana@ic.bashedu.ru. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 75, No. 1, pp. 95–99, January–February, 2002. Original article submitted November 13, 2000; revision submitted March 3, 2001.

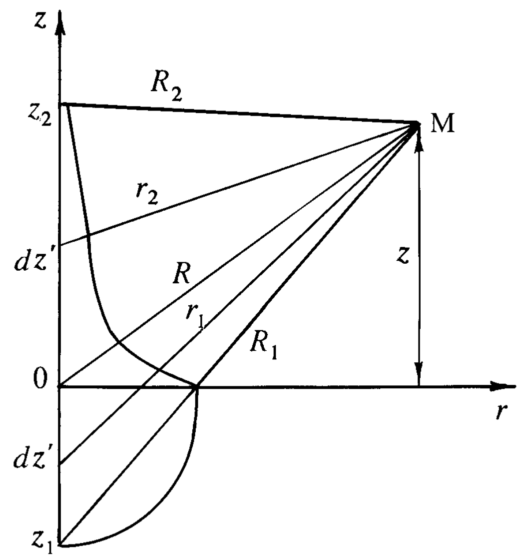

Fig. 1. Diagram of excitation of the asymmetric dipole and distribution of the electric current.

In conformity with the geometry of the problem, for computational investigations we take a cylindrical coordinate system with axial symmetry: the z axis is directed along the well from the lower point of the casing string (point 0 in Fig. 1) to the well mouth (above the point z_2). An electric current along the dipole is distributed following a law which is established from specially conducted experiments:

$$I_z = \begin{cases} I_0 \cos(\beta z) & \text{for } z_1 = -\dfrac{\lambda}{4} < z < 0\,; \\ I_0 \exp(-jkz) & \text{for } 0 < z < z_2 = \dfrac{1}{\alpha}\,, \end{cases} \tag{1}$$

where $k = \beta - j\alpha$.

In solving the electrodynamic problem, we used the method from [2]. The following expressions for the electric and magnetic components of the electromagnetic field strength are obtained:

$$E_z = -\frac{I_0 k}{j\omega\tilde{\varepsilon}4\pi}\left[\frac{\sin(\beta z_1)}{R_1}\exp(-jkR_1) - \frac{j}{R_2}\exp(-jk(z_2+R_2)) + \frac{j}{R}\exp(-jkR)\right];$$

$$H_\varphi = -\frac{I_0}{4\pi r}\left[j\sin(\beta z_1)\exp(-jkR_1) + \exp(-jk(z_2+R_2)) - \exp(-jkR)\right];$$

$$E_r = \frac{I_0 k}{j\omega\tilde{\varepsilon}4\pi r}\left[\frac{(z-z_1)\sin(\beta z_1)}{R_1}\exp(-jkR_1) - \frac{j(z-z_2)}{R_2}\exp(-jk(z_2+R_2)) + \frac{jz}{R}\exp(-jkR)\right];$$

$$R = \sqrt{r^2+z^2}\,;\quad R_1 = \sqrt{r^2+(z-z_1)^2}\,;\quad R_2 = \sqrt{r^2+(z-z_2)^2}\,. \tag{2}$$

In the formulas obtained, the strengths of the electric and magnetic fields are expressed in terms of the current quantity I_0 at the excitation point of the dipole, which is not always convenient. From the practical point of view, it is more preferable to use expressions that are related to the radiator power of the electromagnetic waves N_0 and the radiation resistance R_0 [2]:

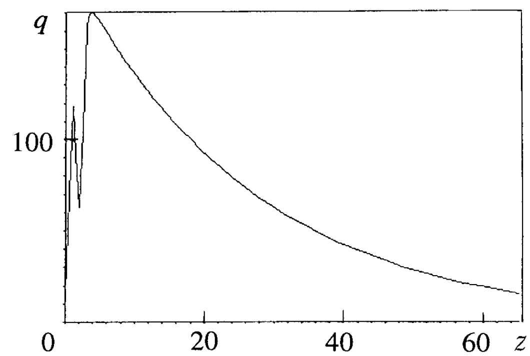

Fig. 2. Distribution of the heat sources in the stratum along the asymmetric dipole at a distance of 0.5 m from the well axis. q, W/m^3; z, m.

$$N_0 = \frac{I_0^2 R_0}{2}\,, \tag{3}$$

where R_0 can be determined by calculating the Poynting vector over the dipole surface and using the expressions derived above for the components of the electromagnetic field. Thus, by means of formula (3), it is possible to express the components of the electromagnetic field strength in terms of the known power of the radiator of electromagnetic waves N_0 and the radiation resistance of the dipole R_0.

The expression for the distributed heat sources through the known strength distribution of the electric and magnetic components of the electromagnetic field has the form [3]

$$q = \frac{1}{2}\,\omega\varepsilon_0\varepsilon'\tan\delta\,(EE^*)\,.$$

Having separated in the expressions for the electric field strength (2) the real and imaginary parts and the orthogonal components E_r and E_z, we finally obtain

$$q = \frac{1}{2}\,\omega\varepsilon_0\varepsilon'\tan\delta\,[(\mathrm{Re}\,E_r)^2 + (\mathrm{Re}\,E_z)^2 + (\mathrm{Im}\,E_r)^2 + (\mathrm{Im}\,E_z)^2]\,. \tag{4}$$

Figure 2 illustrates the distribution of the heat sources along the coordinate z at a distance of 0.5 m from the well axis that is calculated from formula (4) with account for Eq. (2). We carried out the calculations using the following parameters: f = 13.56 MHz, r_0 = 0.08 m, and N_0 = 43.5 kW. The two peaks in the distribution of the heat sources correspond to radiation from the short and long arms of the asymmetric dipole. Along the coordinate r the density of the heat sources decreases exponentially.

Heat and Mass Transfer in the Well–Stratum System. The system of equations describing the heat and mass transfer involves a two-dimensional equation of heat conduction in the stratum and a one-dimensional equation of heat conduction in the well [4]. For the sake of convenience in performing the calculations, the origin of the cylindrical coordinate system is shifted to the stratum base (below the point z_1 in Fig. 1). The equation of heat conduction in the stratum has the form

$$\frac{\partial T_b}{\partial t} = \frac{a_b}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_b}{\partial r}\right) + \frac{\nu(z)\,\rho_f c_f}{C_b}\frac{\partial T_b}{\partial r} + a_b\frac{\partial^2 T_b}{\partial z^2} + \frac{q}{C_b}\,, \tag{5}$$

in which $v(z) = Q(z)/2\pi r\Delta z$.

The electromagnetic waves, propagating in the intertubular well space that envisions a coaxial transmission line, inevitably lose a portion of their energy because of the finite electrical conductivity of the tubes.

This occurs in a very thin skin layer of the latter but due to the smallness of the tube radius it is assumed that the temperature is rapidly equalized over the well cross section. Therefore, for simplification of the calculations we assume that the heat released in the skin layer is uniformly distributed over the well radius. This fact and also the large length of the well tubes relative to their radius allow us to solve the one-dimensional problem of the process of heat transfer in the well that is reduced to the heat-conduction equation with a convective term and heat sources. The heat loss to the rocks which surround the well are taken into account following the Newton law.

The equation of propagation of heat in the well has the form

$$\frac{\partial T_w}{\partial t} = a_w \frac{\partial^2 T_w}{\partial z^2} - \frac{v_w \rho_f c_f}{C_w} \frac{\partial T_w}{\partial z} + \frac{q_w}{C_w} - \frac{\xi (T_w - T_0)}{C_w}, \qquad (6)$$

$$v_w = Q_f / \pi R_5^2 , \quad \xi = \frac{2\kappa_w R_4}{R_4^2 - R_3^2} , \quad \kappa_w = \frac{4 \text{ Nu } \lambda_a}{(8 + \text{Nu}) R_4} .$$

Here Nu = 1, 4, and 10 are the Nusselt numbers that are characteristic of the tube in the dry, moistened, and water-saturated ground, respectively.

Taking into account the geometry of the problem, we obtain the following expression for the "heat sources" over the well axis:

$$q_w = \frac{2\alpha_3 N_g}{\pi R_4^2} \exp(-2\alpha_3 (h_2 - z)) , \quad \alpha_3 = \alpha_1 + \alpha_2 .$$

The consumption of the produced oil $Q(z)$ over the stratum portion Δz and the total running yield of the produced fluid Q_f are determined from the expressions

$$Q(z) = Q_0(z) \frac{\mu_0 \ln \left(\frac{r_c}{r_0} \right)}{\int_{r_0}^{r_c} \frac{\mu_f(r)}{r} dr} , \quad Q_f = \int_0^h Q(z)\, dz .$$

The oil viscosity is temperature-dependent following the law

$$\mu_f(T) = \mu_0 \exp(-\gamma (T - T_0)) .$$

Boundary Conditions. At the well bottom the temperatures and the heat fluxes between the well and the stratum are assumed to be equal. The initial and boundary conditions are taken in the form

$$T_b(r, z, 0) = T_0 , \quad T_w(z, 0) = T_0 ; \qquad (7)$$

$$-\lambda_w \frac{\partial T_w(h_2, t)}{\partial z} = 0 , \quad \lambda_b \frac{\partial T_b(r, 0, t)}{\partial z} = \kappa_b (T_b(r, 0, t) - T_0) ; \qquad (8)$$

$$-\lambda_b \frac{\partial T_b(r, h, t)}{\partial z} = \kappa_b (T_b(r, h, t) - T_0) , \quad \kappa_b = \frac{\text{Nu } \lambda_b}{h} ; \qquad (9)$$

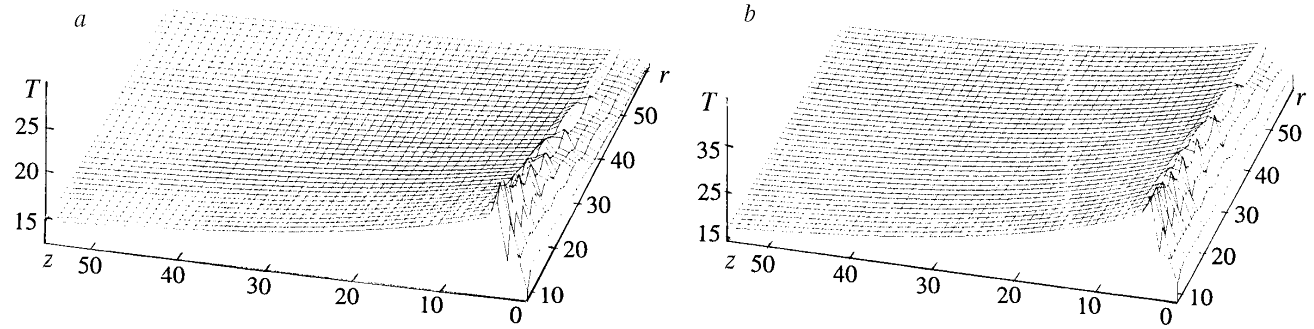

Fig. 3. Temperature distribution in the stratum at the instant of time t = 1 day (a) and t = 10 days (b). T, ^oC; r, m; z, m.

$$T_b(r_m, z, t) = T_0, \quad T_w(h, t) = T_b(r_0, h, t); \tag{10}$$

$$-\lambda_w \frac{\partial T_w(h, t)}{\partial z} = -\lambda_b \frac{\partial T_b(r_0, h, t)}{\partial r}; \tag{11}$$

$$-\lambda_b \frac{\partial T_b(r_0, z < h, t)}{\partial r} = \frac{1}{2\pi r_0} \frac{\partial N_w(z)}{\partial z}, \quad N_w(z) = N_g \exp(-2\alpha_3(h_2 - z)). \tag{12}$$

Analysis of the Calculation Results and Conclusions. The system of equations (5)–(6) with boundary conditions (7)–(12) was solved by the method of finite differences using an implicit scheme. In the calculations we used the following initial parameters: $T_0 = 12^oC$, $R_3 = 0.04$ m, $R_5 = 0.035$ m, $R_4 = r_0 = 0.08$ m, $\varepsilon' = 7.5$, $\tan\delta = 0.05$, $\alpha = 0.0198$ m^{-1}, $\beta = 0.778$ m^{-1}, $\alpha_1 = 0.0003489$ m^{-1}, $\alpha_2 = 0.0001915$ m^{-1}, h = 65 m, H = 240 m, $Q_{f0} = 0.1$ m^3/day, N_g = 20 kW, N_0 = 14.5 kW, Nu = 10, $\lambda_b = 2.646$ W/(m·K), $C_b = 2969$ kJ/(m^3·K), $a_b = 8.91 \cdot 10^{-7}$ m^2/sec, $\lambda_a = 0.0315$ W/(m·K), $\lambda_w = 10.27$ W/(m·K), $C_w = 1620$ kJ/(m^3·K), $a_w = 6.34 \cdot 10^{-6}$ m^2/sec, $c_f = 1200$ J/(kg·K), $\rho_f = 858$ kg/m^3, $\mu_0 = 0.093$ Pa·sec, $\gamma = 0.84$ K^{-1}, and t = 1 and 10 days.

The spatial temperature distributions in the stratum at the instants of time t = 1 and 10 days are shown in Fig. 3. For the convenience of graphical representation of the stratum-bottom zone, we increased the scale of distances along the coordinate r by 100 times. As seen from the figures, the electromagnetic field exerts its action on the stratum over the entire thickness of the stratum but the nonuniformity in the heating of the stratum is observed near the junction point of the dipole arms (the end of the casing string). The greatest nonuniformity in the temperature distribution is seen near the end of the pump-compressor tube, since a standing wave of electric current is located at this end. A slow decrease in the temperature occurs along the casing string (the long arm of the dipole), which makes it possible to heat rather uniformly the entire stratum across the thickness.

The calculations also indicate that the greatest density gradients of the heat sources and temperature along the coordinate r are observed near the end of the pump-compressor tube that is projected below the casing string. Near the latter, these gradients are comparatively small, which allows one to heat approximately uniformly a large volume of the stratum.

The nonuniformity of the temperature distribution in the stratum decreases with time under the action of the heat-conduction process; the temperature at all the points of the stratum rises and the heat front covers an increasingly larger volume of the medium (Fig. 3b).

We should note that the absolute temperatures achieved as a result of the high-frequency electromagnetic action are higher in the well than in the productive stratum. This is explained by the fact that in the

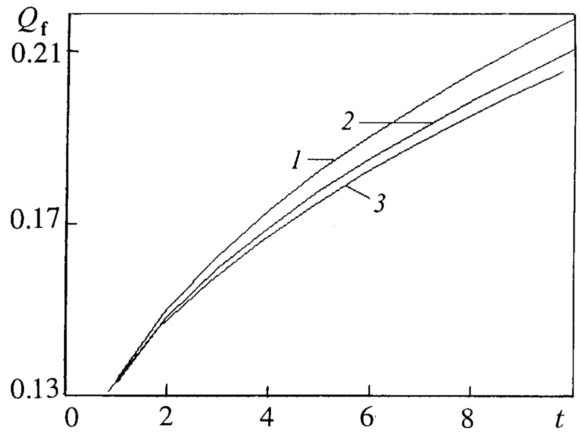

Fig. 4. Dynamics of change in the well yield due to the high-frequency electromagnetic action on the oil stratum: 1) Nu = 1, 2) 4, and 3) 10. Q_f, m^3/day; t, day.

technology suggested the conductor of the electromagnetic energy into the stratum is the well itself, whose tubes are here heated considerably and absorb a substantial portion of the electromagnetic energy. However, this circumstance is positive for the case of deposits of large thickness, since the problem of oil recovery in these deposits is associated not only with the necessity of heating the stratum–bottom zone but also with preservation of high temperatures when lifting the oil to the well mouth, and with prevention of the formation of solid deposits on the tube walls of the well.

The calculations also showed the influence of the surrounding rocks on the temperature distribution and on the yield of the oil produced: with increase in the moisture content of the rocks, the heat loss in the rocks increases and correspondingly the efficiency of the high-frequency heating of the stratum decreases. The dynamics of change in the yield of the well due to the high-frequency electromagnetic action on the oil stratum for N_0 = 43.5 kW and Nu = 1, 4, and 10 is presented in Fig. 4. From this figure it is seen that the higher the value of the Nusselt number (corresponding to the greater moistening of the medium), the slower the well yield grows because of the greater heat leakage into the rocks that surround the stratum. As a whole, however, the difference is not very significant, i.e., within 5%. This is largely explained by the influence of the dimensions (thickness) of the stratum rather than by the degree of water-saturation of the rocks that surround the stratum. The heat loss is, on the whole, not so considerable with respect to the energy introduced into the stratum and the well yield increases more than twice.

Comparison to Pilot-Field Data. For the first time in the Soviet Union, field tests of the method of high-frequency heating for the well-bottom zone of a productive stratum were carried out on well 40/19 at the "Ishimbayneft" Oil- and Gas-Producing Management. The source of the high-frequency electromagnetic energy was a D2-60-type generator which ensured, in an optimal regime, an output vibrational power of 63 kW at a frequency of 13.56 MHz. The main characteristics of the generator were: supply voltage three-phase 380 V, consumed power 105 kW, and water cooling with a water flow rate of 60 liters/min.

The 40/19 well used had the following characteristics: a bored well bottom of 830 m, the casing string diameter 6″, the casing string was lowered to a depth of 379 m, thickness of the open part of the well bottom 451 m, liquid level 792 m, diameter of the pump-compressor tube 2″, running yield was about 3 tons/day, and temperature over the well shaft 287–289 K. The oil contained 2.3% paraffin and 11% resins; the specific weight of the oil was 890 $kg/m^{3;}$, the viscosity of the blanket oil was 20 cP at $T = 20^oC$.

The temperature was measured by a GRT-1 thermograph which was lowered down onto the well bottom through the pump-compressor tube. The temperature was recorded continuously at a fixed depth of

TABLE 1. Dynamics of Change in the Temperature on the Well Bottom

Time of heating, day	0.5	1	2	3	4	5
Increase in temperature, K	10	17	27	33	38	40

650–655 m (in the open part of the well bottom where the radiator operated) during the continuous operation of the generator (the data are given in Table 1).

The field investigations performed have shown that at the modern technical level it is possible to use in practice the method of high-frequency electromagnetic heating for extracting not deeply occurring high-viscosity oils (up to 1000 m) and the results obtained are in qualitative agreement with the calculations carried out for the influence of high-frequency electromagnetic action on the well yield.

The industrial investigations were also conducted on deposits of bitumens in Tatariya. In particular, the experiments on the high-frequency electromagnetic action were conducted in the Yultimir experimental bituminous region (the Sugushly square) of the "Tatneft" Industrial Association [5] through well No. 150. At a distance of 5 m from well No. 150, check well No. 1 was placed. As a result of the action, the temperature in the well bottom was increased to 373 K. Upon switching off the high-frequency installation, the temperature in a period of 3 days decreased to 343 K. This slow cooling indicates the rather deep heating of the productive stratum (up to 5 m) and also the great amount of heat energy that is accumulated by the stratum. On the whole, due to the high-frequency electromagnetic action (in the regime of half power of the high-frequency installation) a 2- to 3-fold increase in the oil yield and an ~3-fold decrease in the supply of the products with water were achieved [6].

The above facts are indicative of the qualitative agreement between the numerical calculations and the results of the pilot-field data. The implementation of the more exact quantitative comparison is difficult because of the absence of the initial physical parameters of the strata that were used for the pilot-field operations.

NOTATION

a_b, thermal diffusivity of the stratum rocks; a_w, volume-averaged thermal diffusivity of the well; ξ, coefficient of heat transfer through the side surface of the casing string to the environment; c_f, specific heat of the oil; C_b, coefficient of heat capacity of the stratum rocks per unit volume; C_w, volume-averaged heat capacity of the well; E_r and E_z, electric components of the electromagnetic field strength along the coordinates r and z; f, cyclic oscillation frequency of the electromagnetic field; h, stratum thickness; h_2, distance from the well mouth to the stratum base; H, occurring depth of the productive stratum; H_φ, magnetic component of the electromagnetic field strength along the cylindrical coordinate φ; Im, imaginary part of the complex quantity; I_0, amplitude of the current at the excitation point of the dipole; j, imaginary unit; k, coefficient of propagation of electromagnetic waves in the stratum; N_0, power of the radiator of electromagnetic waves; N_g, power of the generator of electromagnetic waves that is placed at the well mouth; N_w, power of heat releases on the radiator of electromagnetic waves; t, time; q, density of the distributed heat sources in the stratum; q_w, density of the distributed heat sources in the well; Q, flow rate of the oil drawn on the stratum portion Δz; Q_0, initial (before the high-frequency electromagnetic action) yield of the fluid extracted on the stratum portion Δz; Q_f, total running yield of the fluid extraction; Q_{f0}, total initial yield of the extracted fluid; r, cylindrical coordinate; r_0, dipole radius; r_c, radius of the supply contour of the well; r_m, stratum radius; R, distance from the observation point to the excitation point of the dipole; R_1 and R_2, distances from the observation point to the end of the short and long arm of the dipole; R_3 and R_4, outer radii of the pump-compressor tube and of the casing string; R_5, inner radius of the pump-compressor tube; R_0, resistance to dipole radiation; Re, real part of the complex quantity; T_0, initial temperature and temperature of the rocks surrounding the well and the stratum; T_b, temperature in the stratum; T_w, temperature in the well; tan δ, dielectric loss tangent of the medium; v, filtration velocity of the oil in the stratum; v_w, velocity of motion of the oil in the pump-compressor tube; z, cylindrical coordinate; z_1 and z_2, coordinates of the end of the short (lower pump-compressor tube) and long arm of the dipole; α, damping coefficient of electromagnetic waves in the stratum; α_1 and α_2, damping coefficients of electromagnetic waves in the pump-compressor tube and in the casing string, respectively; α_3, damping coefficient of electromagnetic waves in the well; β, phase coefficient of electromagnetic waves in the stratum; $\hat{\tilde{\varepsilon}}$, complex dielectric permittivity of the medium; ε', relative dielectric permittivity of the medium; ε_0, electric constant; γ, temperature coefficient; κ_w, coefficient of heat exchange between the stratum and the surrounding rocks; κ_b, coefficient of heat exchange between the well and the surrounding rocks; λ, length of the electromagnetic waves in the stratum; λ_a, thermal conductivity of the air; λ_b, thermal conductivity of the stratum rocks; λ_w, thermal conductivity of the well; μ_0 and μ_f, oil viscosity at the initial temperature T_0 and running oil viscosity; ρ_f, oil density; ω, circular frequency of the electromagnetic field. Subscripts: a, air; b, stratum; f, fluid; g, generator; c, supply contour; m, maximum distance under consideration; w, well; *, complex-conjugate quantity.

REFERENCES

1. F. L. Sayakhov, L. A. Kovaleva, and N. M. Nasyrov, *Inzh.-Fiz. Zh.*, **71**, No. 1, 161–165 (1998).
2. G. T. Markov and D. M. Sazonov, in: *Antennas* [in Russian], Moscow (1975), pp. 61–73.
3. F. L. Sayakhov, I. L. Khabibullin, and L. A. Kovaleva, in: *Physics in Bashkortostan* [in Russian], Ufa (1996), pp. 283–295.
4. F. L. Sayakhov, L. A. Kovaleva, and N. M. Nasyrov, *Izv. Vyssh. Uchebn. Zaved.*, *Neft' Gaz*, No. 4, 44–55 (1998).
5. F. L. Sayakhov, G. A. Babalyan, and A. N. Al'met'ev, *Neft. Khoz.*, No. 12, 32–34 (1975).
6. F. L. Sayakhov, R. T. Bulgakov, V. P. Dyblenko, V. S. Deshura, and M. T. Bykov, *RNTS Neftepromysl. Delo*, No. 1, 5–8 (1980).