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PROCESSES OF TRANSFER IN POROUS MEDIA

MATHEMATICAL MODELING OF HIGH-FREQUENCY ELECTROMAGNETIC HEATING OF THE BOTTOM-HOLE AREA OF HORIZONTAL OIL WELLS

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The results of theoretical investigations of the possibility of using intense high-frequency electromagnetic radiation in fields of high-viscosity oils with the aim of intensifying their production have been given. Expressions of the distribution of the electromagnetic field strength and the field of heat sources occurring in an oil bed under the action of high-frequency electromagnetic radiation transferred to the bed through a horizontal well have been obtained. A two-dimensional mathematical model of the process of production of oil through horizontal wells with simultaneous high-frequency electromagnetic action has been developed. The efficiency and profitableness of the method from the viewpoint of the energy balance have been evaluated.

High-frequency electromagnetic heating of dielectrics has been successfully used in various branches of the national economy, including mining, for a comparatively long time. Computational investigations, laboratory work, and field experiments have shown the efficiency of electromagnetic action on the critical area of the beds of oil fields [1–4]. The viscosity of oil is substantially reduced, its rheological properties are improved, and accumulation of paraffin in the critical area of the bed and in the bore hole is avoided.

Processes occurring in vertical-well treatment of the critical area of the bed have been mathematically modeled in existing works on electromagnetic action on oil beds [1, 3]. It is assumed that a coaxial system consisting of a tubing string and a casing string of the well is used for energy supply to a radiator of electromagnetic waves from a ground-based, high-frequency generator. The radiator of electromagnetic waves is an element of the tubing string that extends below the casing string of the well.

Horizontal wells have been used with increasing frequency in recent years in an effort to increase the recovery of oil fields. The efficiency of displacement of oil with the use of horizontal wells is 5 to 30% higher than that of vertical wells. However, the use of horizontal wells does not solve, in principle, the problem of extraction of high-viscosity oils and bitumens. In this case, such methods of action on the bed, as, for example, pumping of the heat-transfer agent or another displacing agent, are difficult and inefficient.

In the present work, we study the possibility of using the energy of a high-frequency electromagnetic field for intensification of the production of oil in the case of development of high-viscosity-oil fields by horizontal wells. Theoretical solution of this problem requires that new mathematical models be formulated. In this case it is impossible, in principle, to use one-dimensional mathematical models and the existing expressions for heat sources.

Distribution of the Electromagnetic Field Strength and the Heat Sources in the Bed. Just as in vertical wells, it is assumed that electromagnetic energy is supplied to the bed from a ground-based, high-frequency generator. Part of this energy is lost in a coaxial transmission line (system consisting of a tubing string and a casing string) because of the finite electrical conductivity of the tube walls.

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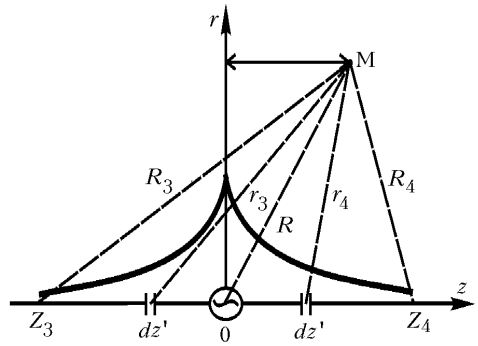

Fig. 1. Diagram of excitation of the symmetric vibrator and of distribution of the electric current.

Since we are investigating the propagation of electromagnetic waves in a bed of fairly large thickness, the reflection of the electromagnetic waves from the external boundaries of the bed can be disregarded, and the oil bed can be considered to be an unbounded medium. Thus, the system in question represents a symmetric vibrator of electromagnetic waves whose arms are the extending part of the tubing string and the exterior surface of the casing string. In view of the considerable length of the arms and the high absorptivity of the ambient medium, it is assumed that the electromagnetic waves propagate without reflection from the ends of the arms, i.e., are traveling waves. The zone of absorption of the energy of the electromagnetic waves by the medium is determined by the expression $Z = 1/\alpha$. The diagram of excitation of the symmetric vibrator (radiator of electromagnetic waves) and distribution of the electric current is shown in Fig. 1. The distribution of the strength of the electric and magnetic components of the electromagnetic field is sought at a certain point of space (observation point) M; R, R_2, and R_3 are the distances from point M to the point of excitation of the radiator and the boundaries of the zone of absorption of electromagnetic waves $Z_3 = -1/\alpha$ and $Z_4 = 1/\alpha$ respectively.

For computational investigations we have adopted a cylindrical coordinate system with axial symmetry: the z axis is directed along the axis of the horizontal well. The electric current along the left-hand and right-hand radiator arms is distributed by the law

$$I_z = \begin{cases} I_0 \exp(jkz) & \text{for} \quad Z_3 < z < 0\,, \\ I_0 \exp(-jkz) & \text{for} \quad 0 < z < Z_4\,. \end{cases} \tag{1}$$

To solve the electrodynamic problem on finding the field of strength of the radiator of electromagnetic waves one divides it into elementary dipoles the electric current in each of which can be considered to be constant in value [5]. The electric and magnetic components of the field of strength of the elementary dipoles are added together and the resulting components of the strength field of the electromagnetic-wave radiator are obtained.

We obtain the strengths of the electromagnetic field of the symmetric vibrator by the method presented in [5]. First we write the expression for the component of the electric field strength that is in parallel to the radiator axis in terms of the vector potential A_z:

$$E_z = \frac{1}{j\omega\dot{\varepsilon}}\left(k^2 A_z + \frac{d^2 A_z}{dz^2}\right), \tag{2}$$

$$A_z = \frac{1}{4\pi}\int_{z=0}^{l} I_{z'}\left(\frac{\exp(-jkr_3)}{r_3} + \frac{\exp(-jkr_4)}{r_4}\right)dz'\,, \quad l = Z = \frac{1}{\alpha}\,. \tag{3}$$

Integration in (3) is from $z' = 0$ to $z' = l$, since we allow for the currents that are symmetrically distant from the center of the radiator and are at the distances $r_3 = \sqrt{r^2 + (z + z')^2}$ and $r_4 = \sqrt{r^2 + (z - z')^2}$ from the observation point M. Substituting (3) into (2) and taking into account that

$$\frac{\partial^2 r_3}{\partial z^2} = \frac{\partial^2 r_3}{\partial z'^2}; \quad \frac{\partial^2 r_4}{\partial z^2} = \frac{\partial^2 r_4}{\partial z'^2},$$

we obtain

$$E_z = \frac{1}{j\omega\dot{\varepsilon}\pi} \int_{z'=0}^{l} \left\{ I_{z'} \frac{\partial^2}{\partial z'^2} \left(\frac{\exp(-jkr_3)}{r_3} + \frac{\exp(-jkr_4)}{r_4} \right) + k^2 I_{z'} \left(\frac{\exp(-jkr_3)}{r_3} + \frac{\exp(-jkr_4)}{r_4} \right) \right\} dz'.$$

Integration of this relation is by parts and leads to the following result:

$$E_z = \frac{1}{j\omega\dot{\varepsilon}\pi} \left\{ \left| I_{z'} \frac{\partial}{\partial z'} \left(\frac{\exp(-jkr_3)}{r_3} + \frac{\exp(-jkr_4)}{r_4} \right) \right|_{z'=0}^{l} - \left| \frac{\partial I_{z'}}{\partial z'} \left(\frac{\exp(-jkr_3)}{r_3} + \frac{\exp(-jkr_4)}{r_4} \right) \right|_{z'=0}^{l} + \right.$$

$$\left. + \int_{z'=0}^{l} \left(\frac{\partial^2 I_{z'}}{\partial z'^2} + k^2 I_{z'} \right) \left(\frac{\exp(-jkr_3)}{r_3} + \frac{\exp(-jkr_4)}{r_4} \right) dz' \right\}. \tag{4}$$

The current at the ends of the radiator is approximately considered to be equal to zero. On the other hand, the expression $\frac{\partial}{\partial z'}\left(\frac{\exp(-jkr_3)}{r_3} + \frac{\exp(-jkr_4)}{r_4} \right)$ for $z' = 0$ is also equal to zero; therefore, the first term on the right-hand side of (4) is equal to zero. In accordance with the formula for the current distribution (1), the third term on the right-hand side of (4) is equal to zero, too. As a result, the component of the electric field strength that is in parallel to the radiator axis has the form

$$E_z = \frac{I_0 k}{\omega\dot{\varepsilon}4\pi} \left[\frac{1}{R_3} \exp(-jk(R_3 - Z_3)) + \frac{1}{R_4} \exp(-jk(R_4 + Z_4)) - \frac{2}{R} \exp(-jkR) \right]. \tag{5}$$

Using the Maxwell equations in differential form in the cylindrical coordinate system and the fact that $E_\varphi = H_r = H_z = 0$, we obtain

$$j\omega\dot{\varepsilon}E_z = \frac{1}{r} \frac{\partial (rH_\varphi)}{\partial r}; \quad j\omega\dot{\varepsilon}E_r = -\frac{\partial H_\varphi}{\partial z}.$$

Hence we find the remaining components of the electromagnetic field strength:

$$E_r = \frac{I_0 k}{\omega\dot{\varepsilon}4\pi r} \left[\frac{2z}{R} \exp(-jkR) - \frac{(z - Z_3)}{R_3} \exp(-jk(R_3 - Z_3)) - \frac{(z - Z_4)}{R_4} \exp(-jk(R_4 + Z_4)) \right], \tag{6}$$

$$H_\varphi = -\frac{I_0}{4\pi r} [\exp(-jk(R_3 - Z_3)) + \exp(-jk(R_4 + Z_4)) - 2\exp(-jkR)],$$

$$R = \sqrt{r^2 + z^2}; \quad R_3 = \sqrt{r^2 + (z + Z_3)^2}; \quad R_4 = \sqrt{r^2 + (z - Z_4)^2}. \tag{7}$$

Here $\dot{\varepsilon} = \varepsilon' \varepsilon_0 (1 - j \tan \delta)$ is the complex permittivity of the medium.

In the expressions (5)–(7) obtained, the components of the field strength E and H are expressed by the value of the current I_0 at the point of excitation of the radiator, which is not necessarily convenient. From the practical viewpoint, it is preferable to use the expressions associated with the power of the radiator of electromagnetic waves N_0 and the resistance of radiation R_0 [5]:

$$N_0 = \frac{I_0^2 R_0}{2} , \tag{8}$$

where, computing the Poynting vector on the radiator surface, we can determine R_0 using the expressions obtained above for the components of the electromagnetic field:

$$R_0 = -\frac{2\pi r_0}{I_0^2} \int_{z_3}^{z_4} [\mathrm{Re}\, E_z (r_0)\, \mathrm{Re}\, H_\varphi (r_0) + \mathrm{Im}\, E_z (r_0)\, \mathrm{Im}\, H_\varphi (r_0)]\, dz .$$

Thus, using formula (8) we can express the components of the electromagnetic field strength by the known power of the radiator of electromagnetic waves N_0 and the resistance of the vibrator radiation R_0.

An expression for distributed heat sources by the known strength distribution of the electric component of the electromagnetic field has the form

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

Separating the real and imaginary parts of the orthogonal components E_r and E_z in expressions (5) and (6) for the electric field strength, we finally obtain

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

Formulation of the Problem. We assume that the radiating horizontal part of the well coincides with the center of the bed horizontally and vertically and has the coordinates Z_2 = 200 m and Z_5 = 500 m. The productive bed represents a horizontal cylinder of radius r_m = 45 m and length L = 700 m. The bed extends from a point with coordinate Z_1 = 0 to the point Z_6 = 700 m (for convenience of the computations the origin of the cylindrical coordinate system is shifted to the left-hand edge of the bed).

A mathematical model of the process is described by a system of two equations — those of piezoconductivity and thermal conductivity. It is assumed that, simultaneously with electromagnetic action on the bed, withdrawal of oil

$$\frac{\partial P}{\partial t} = \frac{k_1}{r} \frac{\partial}{\partial r} \left(\frac{r}{\mu_f (T)} \frac{\partial P}{\partial r} \right) + k_1 \frac{\partial}{\partial z} \left(\frac{r}{\mu_f (T)} \frac{\partial P}{\partial z} \right), \quad k_1 = \frac{k_b}{m\beta_f + \beta_0} ,$$

$$\frac{\partial T}{\partial t} = \frac{a_b}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + a_b \frac{\partial^2 T}{\partial z^2} - \frac{v_r c_f \rho_f}{C_b} \frac{\partial T}{\partial r} - \frac{v_z c_f \rho_f}{C_b} \frac{\partial T}{\partial z} + \frac{q}{C_b}$$

is carried out. The filtration of oil obeys Darcy's law:

$$v_r = -\frac{k_b}{\mu (T)} \frac{\partial P}{\partial r} , \quad v_z = -\frac{k_b}{\mu (T)} \frac{\partial P}{\partial z} .$$

The dynamic viscosity of oil depends on temperature according to the law

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

The flow rate of the produced oil $Q(z)$ on the portion of the well Δz and the total running production rate of the fluid produced Q_f are determined from the expressions

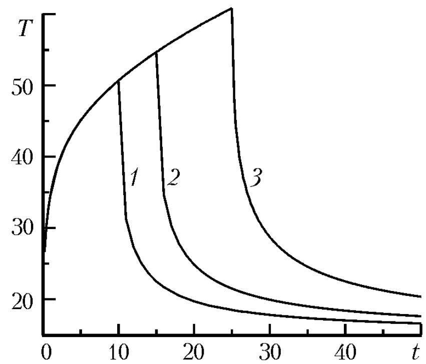

Fig. 2. Dynamics of change in the temperature on the bottom hole of the well in the case of a 10- (1), 15- (2), and 25-day (3) high-frequency action on the bed followed by the withdrawal of a bed fluid without action. T, $^{\rm o}$C; t, days.

$$Q(z) = 2\pi r_0 \Delta z v_r\,, \quad Q_{\rm f} = \int_{Z_2}^{Z_5} Q(z)\, dz\,.$$

The boundary conditions are as follows:

$$T(r, z, 0) = T_0\,; \quad P(r, z, 0) = P_0\,; \quad \left.\frac{\partial T(r_0, z, t)}{\partial r}\right|_{r_0 \to 0} = 0\,; \quad T(r_{\rm m}, z, t) = T_0\,;$$

$$T(r, Z_1, t) = T_0\,; \quad T(r, Z_6, t) = T_0\,;$$

$$\left.\frac{\partial P(r_0, Z_1 \le z \le Z_2, t)}{\partial r}\right|_{r_0 \to 0} = 0\,; \quad \left.\frac{\partial P(r_0, Z_5 \le z \le Z_6, t)}{\partial r}\right|_{r_0 \to 0} = 0\,;$$

$$P(r_0, Z_2 \le z \le Z_5, t) = P_{\rm b}\,; \quad \frac{\partial P(r_{\rm m}, z, t)}{\partial r} = 0\,; \quad \frac{\partial P(r, Z_1, t)}{\partial z} = 0\,; \quad \frac{\partial P(r, Z_6, t)}{\partial r} = 0\,.$$

Analysis of Calculation Results. The calculations were carried out numerically by the finite-difference method according to an implicit scheme for the following initial parameters: N_0 = 20 kW, f = 13.56 MHz, P_0 = 10 MPa, $P_{\rm b}$ = 9 MPa, T_0 = 15$^{\rm o}$C, $a_{\rm b}$ = 8.91·10^7 m^2/sec, $C_{\rm b}$ = 2969 kJ/(m^3·K), $c_{\rm f}$ = 2024 J/(kg·K), $\rho_{\rm f}$ = 894 kg/m^3, μ_0 = 0.2 Pa·sec, γ = 0.042 K^{-1}, r_0 = 0.04 m, m = 0.3, $k_{\rm b}$ = 0.5·10^{-12} m^2, ε' = 7.5, tan δ = 0.05, α = 0.0194 m^{-1}, β = 0.778 m^{-1}, $\beta_{\rm f}$ = 10^{-9} Pa^{-1}, and β_0 = 10^{-10} Pa^{-1}.

In the calculations, we adopted the following operating regimes : 10, 15 and 25 days of high-frequency action on the bed with simultaneous withdrawal of oil followed by the withdrawal of oil without high-frequency action on the bed. We determined the dynamics of change of the temperature on the bottom hole, the pressure and temperature distributions in the bed, and the dynamics of accumulated production of oil throughout the period of its withdrawal. For the sake of comparison we calculated the basic variant — withdrawal of oil from the bed without high-frequency action — for the same initial parameters of the medium.

Figure 2 shows the dynamics of change of the temperature on the bottom hole at different treatment times. It is clear from the figure that relatively low temperature gradients (as compared, for example, to the local electric heating) develop in the bed. This suggests that the energy of the electromagnetic field is quite uniformly distributed in the critical area of the bed owing to the occurrence of volume heat sources.

After the cessation of high-frequency action, the temperature decreases to the initial one during a fairly long time interval — up to 50 days, which contributes to the afterproduction of oil even after the cessation of high-frequency action.

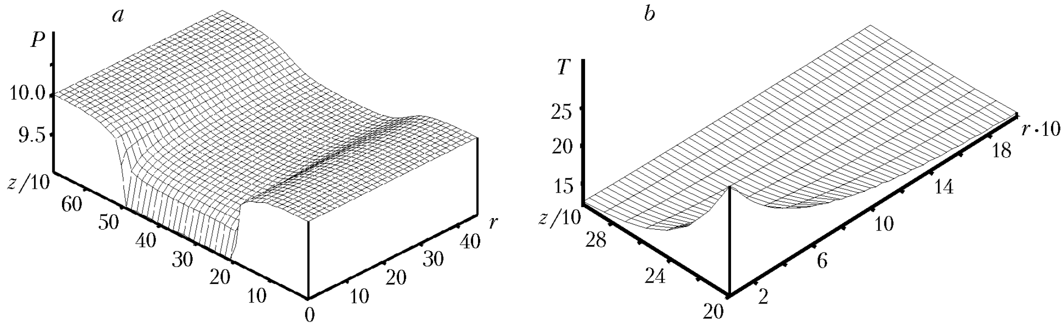

Fig. 3. Pressure (a) and temperature (b) distributions in the oil-saturated bed at the instant of time t = 5 days. P, MPa; r, z, m; T, ^{o}C.

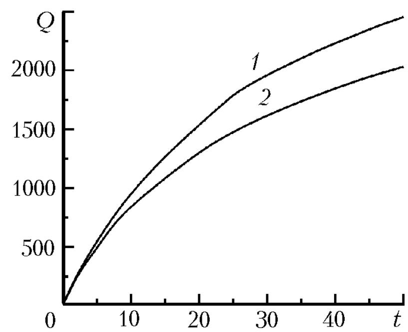

Fig. 4. Dynamics of change in the accumulated production of oil in the case of a 25-day high-frequency action on the bed followed by a 25-day withdrawal of oil without action (1) and in the basic variant (2). Q, m^3; t, days.

Figure 3 gives the pressure and temperature distributions at the instant of time t = 5 days. For convenience of the representation of the critical area of the bed the distance scale of the coordinate z is decreased 10 times, and in Fig. 3b, moreover, the scale of the coordinate r is increased 10 times. Figure 4 shows the dynamics of change in the accumulated production of oil in the case of a 25-day electromagnetic action on the bed followed by a 25-day withdrawal of oil without action (curve 1). The dynamics of change in the accumulated production of oil in the basic variant (curve 2) is also given here for the sake of comparison. From the difference in the values, we can determine the volume of the afterproduced oil in the case of high-frequency action on the bed. As is clear from the figure, this quantity increases with time. Consequently, in further operation of the well, the volume of the afterproduced oil increases.

Evaluation of the Energy Balance. The main problem in introduction of electromagnetic action on the critical area of the bed is in evaluating the efficiency and profitableness of the method from the viewpoint of the energy balance. Below we give a procedure for calculating the energy balance of the technology of electromagnetic treatment of a horizontal well by a VChG3-60/13 commercial unit which has the following technical data: output power 60 kW, operating frequency f = 13.56 MHz, and η_g = 0.67. It is assumed that the distance from the wellhead to the point of excitation of the radiator is 700 m and the tubes of the well are steel with external radii of 0.04 m (tubing string) and 0.08 m (casing string). For these tubes we computed the damping factor of the electromagnetic waves in the intertube space of the well α_{met} according to the procedure of [1] and from the values (measured in [1]) of the electrical conductivity $\sigma_{met} = 0.34 \cdot 10^7 \, \Omega^{-1} \cdot m^{-1}$ and the relative permeability of the tube material μ_{met} = 2.72. From the computed α_{met}, we determined the efficiency of the line of transmission of the electromagnetic energy from the wellhead to the bottom hole: η_l = 0.476 (it was assumed that the intertube space of the well contains air). In evaluating the calculations, we also allowed for the energy loss in the line of electric power transmission from a thermal power station, where the oil produced would conditionally be utilized, to the location of the high-frequency generator. It was adopted that η_{lept} = 0.563.

TABLE 1. Calculation of the Energy Balance of High-Frequency Electromagnetic Action on the Bottom-Hole Area of Horizontal Wells

t, days	M_{aft}, tons	W_{aft}, J	W_{con}, J	$K_{em} = W_{aft}/W_{con}$
10	115	$5.28 \cdot 10^{12}$	$3.66 \cdot 10^{11}$	14.4
15	156	$7.21 \cdot 10^{12}$	$5.5 \cdot 10^{11}$	13.1
25	233	$1.07 \cdot 10^{13}$	$9.17 \cdot 10^{11}$	11.7

In the considered examples of electromagnetic treatment of one well over the period t_{tr}, we determined the volume of the afterproduced oil Q_{aft}. Next, from the known density of oil ρ_f and the oil saturation of the bed S_f we computed the mass of the afterproduced oil $M_{aft} = Q_{aft} S_f \rho_f$ (we adopted $S_f = 0.6$ in the calculations) and determined the conditional afterproduced energy $W_{aft} = M_f G$ from the known calorific value of oil $G = 4.61 \cdot 10^7$ J/kg.

The energy balance was evaluated by the coefficient K_{em}, equal to the ratio of the energy produced as a result of the afterproduction of oil and the energy consumed by the operation of the high-frequency generator. First we determined the total power consumption N_{con} with allowance for η_g, η_l, η_{lept}, $\eta_e = 0.35$, and $\eta_h = 0.75$. As a result, the power consumption was computed with the following expression:

$$N_{con} = \frac{N_0}{\eta_g \eta_l \eta_{lept} \eta_å \eta_h} .$$

The total quantity of the energy consumed in the case considered was determined by multiplication of N_{con} by the time of treatment of the well t_{tr}: $W_{con} = N_{con} T_{tr}$.

To select the optimum time of electromagnetic treatment of the bed we carried out different variants of calculations. Table 1 gives the variants of calculations of the energy balance for 10, 15, and 25 days of treatment of the critical area of the bed with production of oil for 50 days. As is clear from the table, the coefficient of energy balance is $K_{em} > 10$ in all the cases considered. This enables us to consider the method of high-frequency action on the critical area of the bed to be very efficient in treatment of horizontal wells. Furthermore, using one high-frequency generator we can successively treat several wells and produce oil in each of them, utilizing the heat stored in the previous cycle of treatment.

NOTATION

A_z, vector potential, Wb/m; a_b, thermal diffusivity of the bed rocks, m^2/sec; c_f, specific heat of oil, J/(kg·K); C_b, coefficient of heat capacity per unit volume of the bed rocks, J/(m^3·K); dz', linear elements of the radiator of electromagnetic waves (vibrator), m; E_r and E_z, electric components of the electromagnetic field strength along the coordinates r and z, V/m; f, cyclic frequency of oscillations of the electromagnetic field, sec^{-1}; G, calorific value of oil, J/kg; H_φ, magnetic component of the electromagnetic field strength along the coordinate φ, A/m; Im, imaginary part of the complex quantity; $I_{z'}$, amplitude of the current on the linear element of the electromagnetic-wave radiator, A; I_0, amplitude of the current at the point of excitation of the radiator, A; j, imaginary unit; k, coefficient of propagation of electromagnetic waves, m^{-1}; k_1 and k_b, piezoconductivity and permeability of the medium, Pa·m^2 and m^2; K_{em}, energy-balance coefficient in the case of electromagnetic action; l, length of the arm of the symmetric vibrator, m; L, length of the bed, m; m, porosity of the medium; M_{aft}, mass of the afterproduced oil, kg; N_0, power of the electromagnetic-wave radiator, W; N_{con}, total consumption of the electromagnetic-energy power, W; q, density of distributed heat sources, W/m^3; P, pressure, Pa; P_0 and P_b, initial pressure of the bed and pressure in the bed near the horizontal portion of the well, Pa; Q, flow rate of the oil withdrawn on the portion of the bed Δz, m^3/sec; Q_f, total running production rate of the fluid produced, m^3/sec; Q_{aft}, volume of the afterproduced oil, m^3; r, cylindrical coordinate, m; r_0, radius of the horizontal portion of the well (radiator), m; r_3 and r_4, distances from the linear elements of the electromagnetic-wave radiator to the observation point, m; r_m, radius of the bed, m; R, distance from the observation point to the point of excitation of the radiator, m; R_3 and R_4, distances from the observation point to the "ends" of the radiator, m; R_0, resistance of the vibrator radiation, Ω; Re, real part of the complex quantity; S_f, oil saturation of the bed; T_0 and T, initial and running temperatures of the bed, ^{o}C; t, time, sec; t_{tr}, time of electromagnetic treatment of the bed, sec; tan δ, dielectric loss tangent of the medium; v_r and v_z, components of the rate of filtration of oil along the coordinates r and z, m/sec; W_{aft}, afterproduced energy in the case of electromagnetic action on the bed, J; W_{con}, energy consumption in the case of electromagnetic action on the bed, J; Z, length of the zone of absorption of the energy of electromagnetic waves by the medium, m; z, cylindrical coordinate, m; z', coordinate of the linear element of the electromagnetic-wave radiator, m; Z_1, coordinate of the beginning of the bed, m; Z_2, Z_5, coordinates of the beginning and the end of the horizontal portion of the well, m; Z_3, Z_4, coordinates of the "ends" of the electromagnetic-wave radiator, m; Z_6, coordinate of the end of the bed, m; α_{met}, damping factor of electromagnetic waves in the intertube space of the well, m^{-1}; α and β, damping factor and phases of electromagnetic waves in the bed, m^{-1}; β_f and β_0, compressibility of oil and of the skeleton of the bed rock, Pa^{-1}; $\dot{\varepsilon}$, complex permittivity of the medium, F/m; ε', relative permittivity of the medium; ε_0, electric constant, F/m; γ, temperature coefficient, K^{-1}; η_e, η_g, η_l, and η_{lept}, efficiencies of the thermal power station, the electromagnetic-wave generator, the line of transmission of electromagnetic energy from the wellhead to the bottom hole, and the line of electric power transmission from the thermal power station, where the oil produced will conditionally be utilized, to the location of the high-frequency generator; η_h, heat-loss factor of electromagnetic energy in the well, associated with the oxidation and contamination of the tubing-string surface and the water cutting of production; φ, cylindrical coordinate, rad; μ_0 and μ_f, viscosity of oil at the initial temperature T_0 of the bed and running viscosity of oil, Pa·sec; μ_{met}, permeability of the tube material, H/m; ρ_f, density of oil, kg/m^3; σ_{met}, specific electrical conductivity of the tube material, $\Omega^{-1}\cdot$m^{-1}; ω, circular frequency of the electromagnetic field, rad/sec. Subscripts: b, bed; aft, afterproduced oil and electric energy; e, power station; em, electromagnetic; f, oil; g, generator; l, line of electric power transmission from the wellhead to the bottom hole; lept; line of electric power transmission from the thermal power station, where the oil produced will conditionally be utilized, to the location of the high-frequency generator; tr, treatment of the bed by the electromagnetic field; con, energy consumption; h, heat loss of electromagnetic energy in the well, associated with the oxidation and contamination of the tubing-string surface and the water cutting of production; met, metal; m, maximum distance in question along the coordinate r; z', coordinate of a point of the vibrator; 0, in the symbols I_0, N_0, and R_0, is related to the point of excitation of the vibrator, in the symbols P_0 and T_0, denotes the initial state of the medium; *, sign of the complex conjugate quantity.

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