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HEATING AND MELTING OF ASPHALT–PARAFFIN PLUGS IN OIL-WELL EQUIPMENT USING AN ELECTROMAGNETIC RADIATION SOURCE OPERATING IN A PERIODIC MODE

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This paper considers the elimination of asphalt–paraffin plugs in wellbore equipment using a high-frequency radiation source which is energized and de-energized periodically. The dynamics of melting of plugs is analyzed numerically. The time of removal of plugs is determined with variation in the off-duty ratio of the operating cycle of the high-frequency oscillator and the time of its continuous operation in a cycle.

Introduction. At present, the high-frequency (HF) method holds much promise for elimination of paraffin plugs in oil-well and pipeline equipment [1–4]. This is due to its rather simple clean technological implementation and high effectiveness. In contrast to other methods of breaking asphalt–paraffin plugs, the HF method uses a volumetric nature of heat release and melting of asphalt–paraffin plugs [3, 4]. In this case, most of the heat is expended in implementation of the phase transition, whereas in the other thermal methods, the energy input is expended mainly in overheating of the surface layers of oil and is lost as a result of heat exchange with the ambient medium.

For optimal operation of a "microwave furnace," it is necessary to select the radiation frequency such that the power supplied to the HF source is used in heating and fusion of a plug with maximum efficiency [3, 4]. However, even in the optimal regime, the operating time of the HF generator is a few hours to tens of hours, depending on the radiation source power and the volume of the paraffin plug. Thus, a HF generator with a power of 10 kW and a frequency of $f = 10$ MHz eliminates a 100-m-long paraffin plug in an oil well (the radius of the inner pipe of wellbore equipment $R_1 = 1.8$ cm and the radius of the outer pipe $R_2 = 5$ cm) within 34 h of continuous-wave operation [4]. It is clear that continuous-wave operation of a HF electromagnetic radiation source for a long time involves technical difficulties. Therefore, there is the question of the sensitivity of the HF method for eliminating paraffin plugs when the supply is disconnected for a long time because of faulty operation or preventive work.

The present paper deals with the melting of paraffin plugs by a HF oscillator energized and de-energized periodically.

Basic Physical Assumptions and Mathematical Model of the Process. A wellbore is a system of two coaxial metal pipes. From a physical viewpoint, the wellbore equipment is equivalent to a coaxial transmission line. Let us consider a coaxial line whose internal space is filled with a dielectric (paraffin) with permittivity ε. For a mathematical description of the process, we use cylindrical coordinates (r, φ, z). We assume that the longitudinal dimension of the paraffin plug is $0 \leqslant z \leqslant H$ and its cross-sectional dimension is such that the plug completely fills the space between the pipes. The inner radius of the coaxial line is denoted by R_1 and its outer radius is denoted by R_2. In the plane $z = 0$, there is a source of electromagnetic radiation with frequency f and power P.

The operation law of the HF source is described by the function $\varphi(t)$. In the case of periodic operation, the function $\varphi(t)$ is defined by

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$$\varphi(t) = \begin{cases} 1, & n\tau < t < \tau_* + n\tau, \\ 0, & \tau_* + n\tau < t < (n+1)\tau, \end{cases} \tag{1}$$

where τ is the cycle time and τ_* is the duration of continuous-wave operation of the electromagnetic radiation source in a cycle. The electromagnetic wave propagating along the coaxial line attenuates, which leads to energy release in the dielectric medium. The energy density is given by [4]

$$Q = \frac{P\varphi(t)}{2\pi\,\ln(R_2/R_1)}\,\frac{\alpha_V}{r^2}\,\exp\left(-(\alpha_V + \alpha_S)z\right), \tag{2}$$

$$\alpha_V = \frac{2\pi f}{c}\,\sqrt{\varepsilon'}\,\delta, \qquad \delta = \frac{\varepsilon''}{\varepsilon'}, \tag{3}$$

$$\alpha_S = \frac{1}{2}\,\sqrt{\varepsilon'}\,\sqrt{\frac{f}{\sigma}}\,\frac{1/R_1 + 1/R_2}{\ln(R_2/R_1)}, \tag{4}$$

where ε' and ε'' are the real and imaginary parts of the complex permeability $\varepsilon = \varepsilon' + i\varepsilon''$, c and is the speed of light in vacuum, and σ is the conductivity of the metal of which the wellbore pipes are made. In contrast to the expression given in [3], expression (2) takes into account the actual electromagnetic-field distribution over the cross section of the coaxial line and additional wave attenuation in the metal walls. The coefficient α_V describes the volume attenuation of the electromagnetic wave due to the presence of the imaginary part of the complex permeability of paraffin, and α_S is the electromagnetic-wave attenuation in the metal walls of coaxial pipes due to the finite conductivity of the metal [5], by virtue of which energy is released on the inner surface of the metal conductors. The surface density of the thermal power released in the pipe walls is defined by

$$q_i = \sqrt{\varepsilon'}\,\sqrt{\frac{f}{\sigma}}\,\frac{P\varphi(t)}{4\pi R_i^2\,\ln(R_2/R_1)}\,\exp\left(-(\alpha_V + \alpha_S)z\right) \qquad (i = 1,\, 2). \tag{5}$$

Here $i = 1$ and 2 correspond to the inner and outer conductors, respectively.

The temperature distribution in the plug is described by the heat-conduction equation. In the numerical solution below, the method of through counting [6] is used and, therefore, the heat-conduction equation is written in general form without explicit separation of phases:

$$\rho c_T\,\frac{\partial T}{\partial t} = \frac{1}{r}\,\frac{\partial}{\partial r}\Big(\lambda r\,\frac{\partial T}{\partial r}\Big) + \frac{\partial}{\partial z}\Big(\lambda\,\frac{\partial T}{\partial z}\Big) + Q(r,z,t). \tag{6}$$

Here ρ, c_T, and λ are, respectively, the density, heat capacity, and thermal conductivity of high-paraffin oil. The density and thermal conductivity are considered independent of temperature, and the heat capacity has a δ-shaped singularity at the phase-transition temperature T_s:

$$c_T = c_0 + L\delta(T - T_s). \tag{7}$$

Here L is the latent heat of the phase transition and $\delta(x)$ is the Dirac delta function.

The heat-conduction equation (6) should be supplemented by boundary conditions. At the plug end $z = 0$, we impose boundary conditions in the form of heat convection under Newton's laws

$$\lambda\,\frac{\partial T}{\partial z}\Big|_{z=0} = æ_1[T(r,0,t) - T_0], \tag{8}$$

where T_0 is the initial temperature of the paraffin equal to the ambient temperature. At the remote end of the plug $z = H$ there is no heat exchange:

$$\lambda\,\frac{\partial T}{\partial z}\Big|_{z=H} = 0. \tag{9}$$

On the side surface of the outer cylinder $r = R_2$, the boundary conditions is specified in the form of the heat-convection law with a different heat-exchange coefficient æ. In this case, surface heat release due to electromagnetic-wave attenuation in the metal pipe walls is taken into account (5):

$$-\lambda\,\frac{\partial T}{\partial r}\Big|_{r=R_2} = æ[T(R_2,z,t) - T_0] - q_2(z,t). \tag{10}$$

The inner surface of the coaxial line $r = R_1$ is assumed to be heat insulated. With allowance for surface heat release, the boundary condition on the inner surface is given by

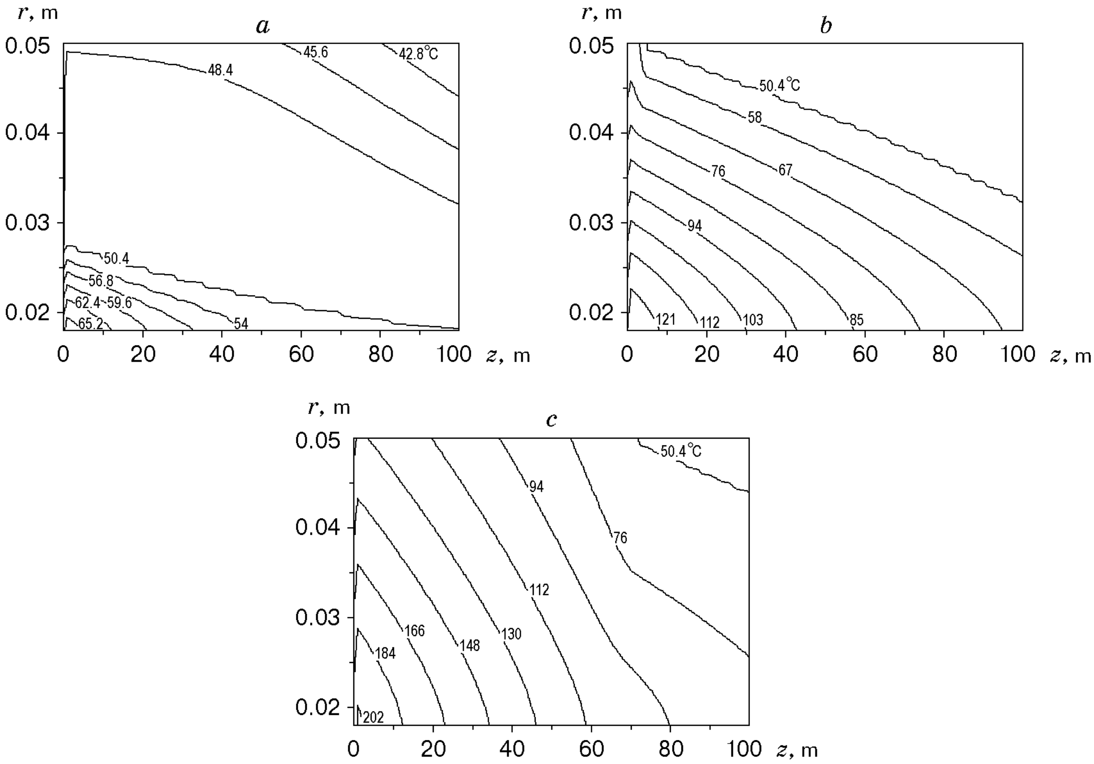

Fig. 1. Position of isotherms for continuous heating regime at $t = 2.5$ (a), 7 (b), and 12 h (c).

$$\lambda \frac{\partial T}{\partial r}\Big|_{r=R_1} = -q_1(z,t). \tag{11}$$

Thus, the heat-conduction equation (6), boundary conditions (8)–(11), and the expressions for the power density of the volumetric and surface heat releases completely describe the variation of temperature distribution in the wellbore equipment in the case of periodic heating of the plug by the HF source described by the function $\varphi(t)$. It should be noted that the physical pattern of heating and melting of the plug depends weakly on the boundary conditions at the ends because heat is lost primarily through the side surface of the outer pipe.

Numerical Simulation of the Elimination of a Paraffin Plug. To simulate the elimination of a paraffin plug, we assume that an oil well is equipped with a pumping-compressor pipe of inner radius $R_1 = 0.018$ m and outer radius $R_2 = 0.05$ m and the paraffin plug has a length of $H = 100$ m. The thermal parameters of high-paraffin oil are as follows: $\rho = 950$ kg/m^3, $c_0 = 3$ kJ/(kg $\cdot$ K), $T_s = 50°$C, $L = 300$ kJ/kg, and $\lambda = 0.125$ W/(m $\cdot$ K). The ambient temperature is $T_0 = 20°$C. The real and imaginary parts of the complex dielectric constant ε are assumed to depend weakly on the operating frequency of the HF source. In the numerical calculations, we use $\varepsilon = 2.3$ and $\delta = \varepsilon''/\varepsilon' = 0.021$ [3]. At the left end of the pipe ($z = 0$), the heat-exchange coefficient $æ_1 = 0.2$ W/(m$^2 \cdot$ K), and on the side surface of the outer cylinder, $æ = 2.5$ W/(m$^2 \cdot$ K). The indicated value æ corresponds to thermal contact of the outer pipe of the wellbore equipment with dry soil [3].

In the numerical solution of Eq. (6), δ-function in the expression for heat capacity (7) was approximated by a step with a width of $\Delta = 0.8°$C. Thus, it is assumed that in the temperature range $|T - T_s| < \Delta/2$, melting proceeds in each elementary volume, i.e., the fluid and solid phases exist simultaneously. Ignoring thermal diffusivity, from Eq. (6), we obtain the lower bound for the melting time:

$$\Delta t_{\rm ph} \sim L\rho/Q. \tag{12}$$

As might be expected, the melting time does not depend on the method of "spreading" the δ-function. However, on the one hand, the width of the melting zone Δ should not be very small, in order that the melting time far exceed the time step of the grid. On the other hand, the width of the step Δ of the "spread" δ-function should not be too large because, otherwise, there are large errors in determining the position of the melting front.

The melting time is minimal on the surface of the inner core pipe near the section $z = 0$. Substituting the calculated parameter values into (12), we obtain $\Delta t_{\rm ph}^{\rm min} = 4.3 \cdot 10^3$ sec.

TABLE 1

N	τ_*, h	t_{tot}, h	t', h	N	τ_*, h	t_{tot}, h	t', h
	2.00	14.75	12.75		2.00	20.00	14.00
	1.00	16.00	13.00		1.00	20.00	14.00
1.25	0.50	16.00	13.00	1.5	0.50	20.50	14.00
	0.25	16.00	13.00		0.25	20.75	14.00
	0.125	16.00	12.875		0.125	20.75	13.875
	2.00	17.50	13.50		2.00	33.50	17.50
	1.00	17.50	13.50		1.00	34.25	17.25
1.33	0.50	17.25	13.25	2	0.50	34.50	17.50
	0.25	17.25	13.00		0.25	34.00	17.00
	0.125	17.50	13.125		0.125	33.75	16.875

Equation (1) was solved numerically using an explicit difference scheme on a uniform rectangular grid $\Delta t = 3.6$ sec, $\Delta r = 8 \cdot 10^{-4}$ m, and $\Delta z = 0.1$ m.

The goal of the numerical analysis is to study the effect of the energizing period of the HF source (cycle time) τ and the time of its continuous operation τ_* (in a cycle) on the total time required to eliminate the paraffin plug and the total operation time of the HF source. The total operation time of the HF source determines the expenditure of energy at fixed power.

Obviously, periodic energizing and de-energizing of the HF source can have a significant effect on the elimination of the paraffin plug if the time interval during which the HF source is energized is close to or larger than the characteristic time of thermal diffusion $c\rho X^2/\lambda$ (X is the characteristic transverse or longitudinal dimension of the system). Otherwise, the problem of plug melting can be treated as the problem with a continuous-wave HF source [4] but with equivalent power equal to the power averaged over the operation period of the HF radiation source.

All calculations were performed for an electromagnetic-radiation source with a power of $P = 20$ kW and a frequency of $f = 10$ MHz.

Figures 1–3 shows isotherms of the paraffin plug for various times. Figure 1 corresponds to the continuous-wave mode, and Figs. 2 and 3 correspond to periodic modes with continuous-wave operation times of the HF source $\tau_* = 2$ and 1 h and values of the off-duty ratio $N = \tau/\tau_* = 1.5$ and 2, respectively. The characteristic times for the continuous-wave mode are chosen as follows: Fig. 1a shows the time during which the plug melts over the entire length of the channel, Fig. 1b shows the time during which the plug melts over the entire cross section at the point $z = 0$, and Fig. 1c shows the time required to eliminate the paraffin plug. For the periodic modes of operation of the HF source, the times in Fig. 2a and b and in Fig. 3a and b are chosen from the same considerations as in Fig. 1a and b. Figures 2c and 3c correspond to the time of elimination of the paraffin plug in the continuous-wave mode, and Figs. 2d and 3d correspond to the time of elimination of the paraffin plug.

From analysis of Figs. 1–3 it follows that operation of the HF source in the periodic modes leads to a more uniform heating of the plug and melted paraffin layers. The maximum temperature $T_{\max}$ in the tested sample is well below that for heating of the plug by the HF source operating in the continuous-wave mode. At an off-duty ratio of $N = 2$ and $\tau_* = 1$ h, $T_{\max} = 160$°C, and in the continuous-wave mode, $T_{\max} = 220$°C. The total time of elimination of the paraffin plug increases nonlinearly with increase in the off-duty ratio: $t_{\text{tot}} = 20$ h for $N = 1.5$ and $t_{\text{tot}} = 34.25$ h for $N = 2$. In this case, the operation times of the HF source are $t' = 14$ and 17.25 h, respectively. In the continuous-wave mode of the HF source, the paraffin plug is eliminated within 12 h.

We note that with further increase in the off-duty ratio, the time of elimination of the paraffin plug increases considerably and at $N = 3$ ($P = 20$ kW), and it is impossible to achieve complete melting of the plug. There is a stationary state in which the heat release is compensated for by heat losses.

Table 1 gives results of numerical analysis for elimination of paraffin plugs by the HF source operating in periodic modes for various values of the off-duty ratio and the time of operation of the HF source in a cycle.

To illustrate thermal diffusion and heat losses in the time interval between the energizing and de-energizing of the HF source, Fig. 4 shows temperature distributions over the volume of the paraffin plug at $N = 2$ and $\tau_* = 2$ h. It is evident that over the time interval in which the HF source is switched off, the maximum temperature decreased by 38°C and the temperature distribution became more uniform. The phase-transition surface practically did not change position over the indicated time. A similar situation is observed for the case with $N = 2$ and $\tau_* = 1$ h.

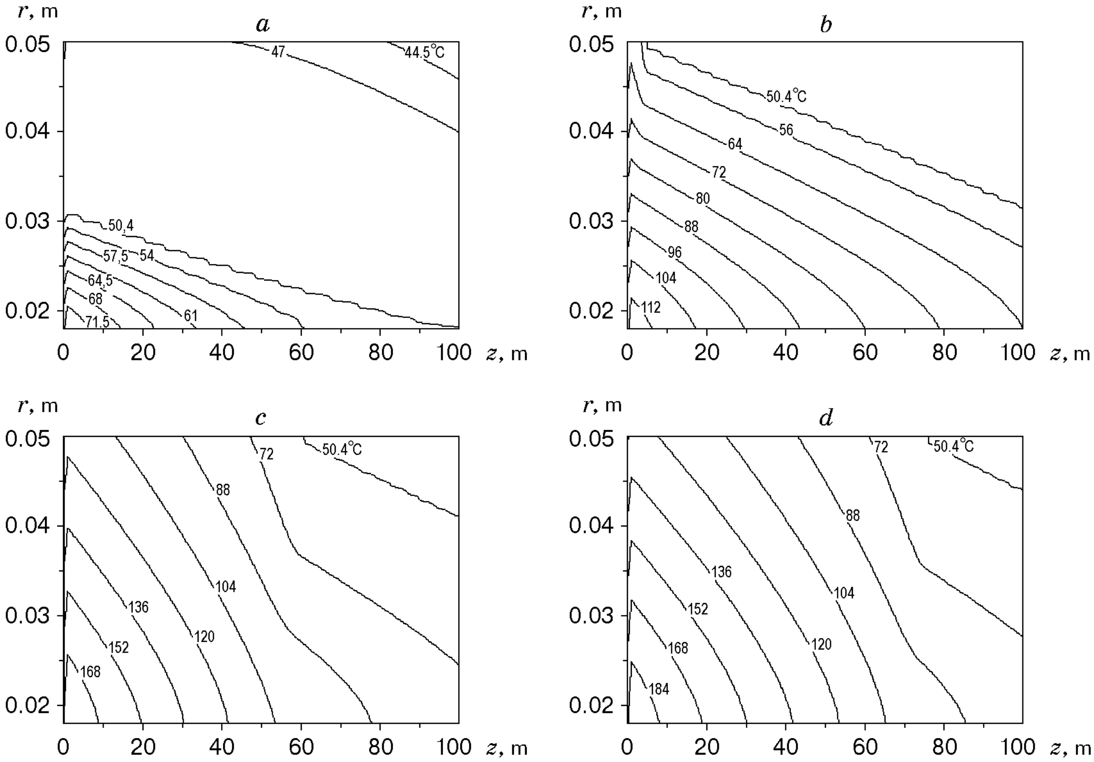

Fig. 2. Position of isotherms at an off-duty ratio of $N = 1.5$ ($\tau_* = 2$ h) and $t = 4$ (a), 10.25 (b), 17 (c), and 20 h (d).

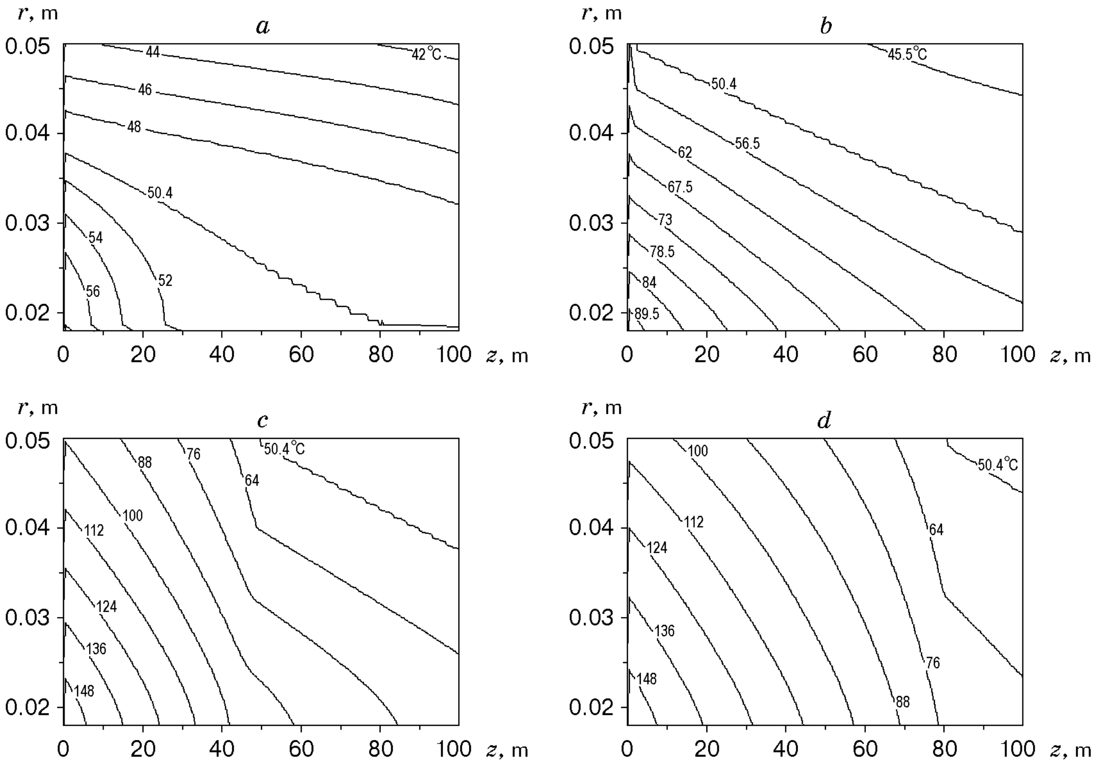

Fig. 3. Position of isotherms at an off-duty ratio of $N = 2$ ($\tau_* = 1$ h) and $t = 8$ (a), 14.25 (b), 23 (c), and 34.25 h (d).

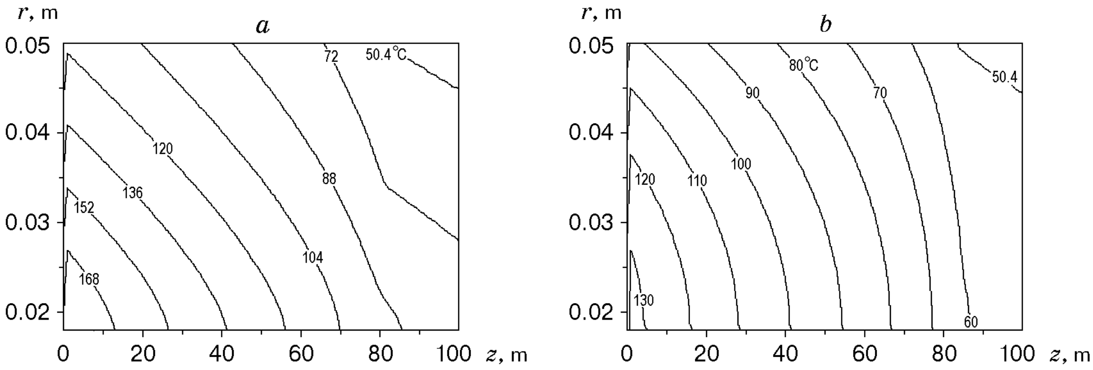

Fig. 4. Dynamics of cooling of the medium in the time interval between two pulses of the HF signal: $t = 34$ (a) and 36 h (b).

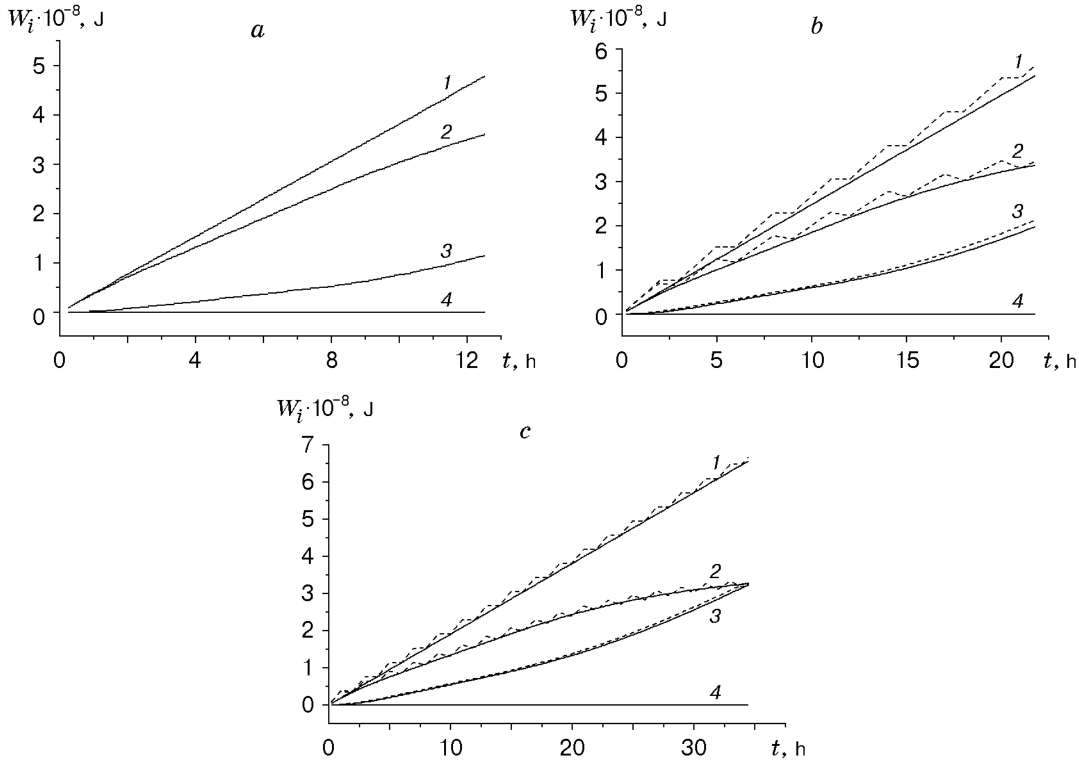

Fig. 5. Time dependences of energy characteristics: curves 1–4 refer to W_1, W_2, W_3, and W_4, respectively; (a) continuous-wave mode; (b) solid curves correspond to the continuous-wave mode at $P = 13.33$ kW and dashed curves correspond to the periodic mode ($N = 1.5$ and $\tau_* = 2$ h); (c) solid curves refer to the continuous-wave mode at $P = 10$ kW and dashed curves refer to the periodic mode ($N = 2$ and $\tau_* = 1$ h).

To determine the efficiency of the electromagnetic radiation source, it is necessary to know how its energy is expended. The energy balance that follows from the differential heat-conduction equation (6) with boundary conditions (8)–(11) and expressions (2)–(5) for volumetric and surface losses of electromagnetic-wave energy is written as

$$W_2 = W_1 - W_3 - W_4,$$

where

$$W_1 = P(1 - \exp(-\lambda H)) \int_0^t \varphi(t')\, dt', \qquad W_2 = \rho \int dV \int_{T_0}^{T} c(T')\, dT',$$

$$W_3 = 2\pi æ R_2 \int_0^t dt \int_0^H [T(r = R_2, z, t) - T_0]\, dz, \quad W_4 = 2\pi æ_1 \int_0^t dt \int_{R_1}^{R_2} r[T(r, z = 0, t) - T_0]\, dr.$$

The quantities W_i $(i = 1, \ldots, 4)$ have the following physical meaning: W_1 is the energy absorbed in the volume of the paraffin plug and the metal walls of the coaxial line, W_2 is the enthalpy of the system, W_3 are the energy losses due to heat exchange on the surface of the outer pipe, and W_4 are the energy losses at the end of the paraffin plug.

Figure 5 shows time dependences of the energy characteristics W_i for the continuous-wave and periodic modes. It is evident that at an off-duty ratio of $N = 2$, the heat losses are comparable to the enthalpy of the system at the end of elimination of the plug. Upon complete elimination of the plug, approximately half of the thermal energy released in the plug is dispersed into the ambient medium. In a continuous-wave mode with $N = 1.5$, these losses are much smaller.

From Fig. 5 it follows that in the continuous mode, approximately 40% of the HF oscillator energy is expended in useful work. For an off-duty ratio $N = 1.5$, 35% of the input energy goes in elimination of the paraffin plug, and for $N = 2$, this value is less than 30%.

It was noted above that the action of electromagnetic radiation on a paraffin plug under periodic operating conditions of the HF source can be described as the action of a wave with constant amplitude and power averaged over the operation period. For comparison, for a HF source with a power of $P = 13.33$ kW operating in the continuous-wave mode and a HF source with $P = 10$ kW in the continuous-wave mode, the time characteristics W_i are shown by solid curves in Fig. 5b and Fig. 5c respectively. It is evident that for a HF radiation source working in a periodic mode and a source working continuously with power equal to the average power of the "periodic" source, the times of elimination of paraffin plugs almost coincide.

Conclusions. The analysis of the elimination of paraffin plugs in the oil-well equipment by electromagnetic radiation from a HF source operating in a periodic mode showed that the total time require to eliminate a plug depends appreciably on the HF radiation power and the off-duty ratio of its operating cycle. At fixed power of a HF source, the total time of elimination of a plug depends nonlinearly on the off-duty ratio. The total time of operation of the HF source increases with increase in the off-duty ratio and depends weakly on the operation time in a cycle. There is a threshold value of the off-duty ratio for which complete melting of a paraffin plug is never reached. Thus, for a power of $P = 20$ kW and an off-duty ratio of $N = 3$, it is impossible to completely eliminate a 100-m-long plug in the standard equipment of a well.

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