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HIGH-FREQUENCY METHOD OF REMOVAL OF PARAFFIN PLUGS IN THE EQUIPMENT OF OIL WELLS AND OIL PIPELINES

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The processes of heating and melting of paraffin plugs in the shafts of oil wells and in oil pipelines by high-frequency electromagnetic radiation have been investigated. The evolution of the temperature fields in the volume of the plugs has been investigated for various physical conditions and various geometries of the plugs. The times of melting of a through channel in a plug and the times of its complete liquidation have been determined. Unlike the works carried out earlier, elimination of paraffin plugs was investigated with regard for the nonuniformity of the distribution of high-frequency power over the cross section of a plug and the absorption of a high-frequency wave in the metallic walls of a well or a pipeline.

Introduction. In the process of operation of oil wells and pipelines, asphalt paraffin (wax) deposits are formed on the inner surface of the pipes under certain conditions (temperature, pressure). Sometimes they can completely plug a well or a pipeline and stop the production or transportation of oil. The lengths of resin-wax plugs can reach high values — of the order of 100–1000 m. A number of methods of cleaning of asphalt-paraffin deposits and of prevention of the formation of oil plugs and their removal have been developed at present. These methods include:

1) heating of the portions of wells or pipelines in which asphalt-paraffin deposits have been formed to the temperature of their melting; the heating is usually effected by hot water (vapor) or by ordinary electric heaters;

2) mechanical cleaning of pipelines.

These methods differ from each other, but their common characteristic is that they are expensive and difficult to implement, which sends one in search of new, less expensive and more productive means of preventing the formation of paraffin plugs (slugs) and of destroying them. One of these means is the use of powerful microwave radiation.

From the viewpoint of high-frequency electrodynamics, shafts of wells and pipelines represent transmission lines (coaxial lines, cylindrical waveguides) for electromagnetic waves. The phase and group velocities of electromagnetic waves and their attenuation are determined by the type of waves, the material of the pipeline walls, and the dielectric properties of hydrocarbons. Having directed the high-frequency power from an external generator to a plug, one can heat it to the melting temperature of paraffin and thus remove the barrier [1–5]. An important advantage of the high-frequency method of heating of plugs is its volumetric character, since high-frequency electromagnetic waves can penetrate into the plug material to a large depth. Moreover, by measuring the level of high-frequency-generator power and the electromagnetic-radiation frequency, one can control the heating processes since the permittivity and the dissipation factor of the plug material [6] are dependent on the radiation frequency and the temperature.

In the present work, we have investigated the processes of heating and melting of a paraffin plug filling the entire cross section of a portion of an oil well or an oil pipeline.

Removal of Paraffin Plugs in Oil Wells. Earlier, the processes of heating and melting of paraffin plugs in an oil well were considered in [4]. In this case, the model of a uniform distribution of a high-frequency field over the cross section of a shaft was used. The ohmic absorption of the high-frequency power in the walls of wells, which can lead to an additional attenuation of electromagnetic radiation in the process of its propagation and accordingly to the heating of the walls, was not taken into account. In actual practice, for the TEM (transverse electromagnetic) waves

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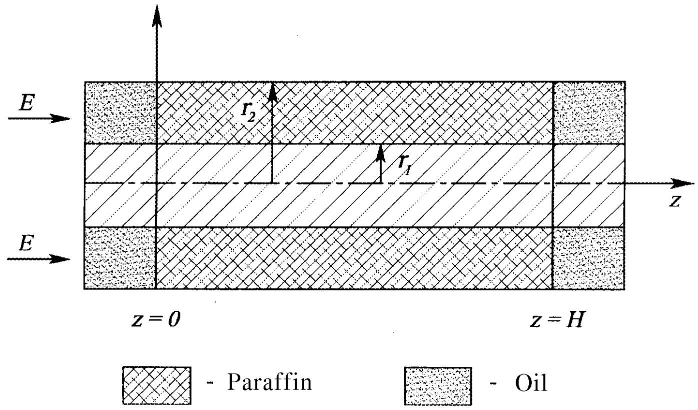

Fig. 1. Diagrammatic picture of the portion of the equipment of a paraffin-plugged oil well, $0 \le z \le H$.

(cable waves) considered the distribution of high-frequency power over the cross section is highly nonuniform. Taking account of the nonuniform radial distribution of high-frequency power allows one to determine the qualitative and quantitative features of the heating and melting of a plug in the shaft of a well [5]. Moreover, below we consider additional attenuation of the TEM waves in the well, which is due to the loss of the high-frequency power in the walls of the well shaft. Dissipation of the high-frequency power in the steel pipe walls leads to the heating of the walls, and, since the steel walls are in thermal contact with a paraffin plug, there appears an additional channel of heating of the plug.

Mathematical Model and Method of Solution. The shaft of a well represents a system of two coaxial steel pipes with round cross sections. The space between the pipes is filled with a dielectric plug of solidified highly paraffinic oil. The shaft of the well can be represented diagrammatically as a coaxial transmission line (Fig. 1). In the plug, an external high-frequency generator forms a flux of the high-frequency energy of a TEM wave with electromagnetic field components

$$E_r = -\frac{U}{r}\frac{1}{\ln (r_2/r_1)} \exp (-i\omega t + ikz - \alpha z/2) + \text{c.s.}\,, \quad H_\varphi = \sqrt{\frac{\varepsilon_0 \varepsilon_r}{\mu_0}}\, E_r\,, \tag{1}$$

where $k = \omega \sqrt{\varepsilon_0 \mu_0 \varepsilon_r}$ and $\alpha = \alpha_v + \alpha_s$. For the absorption coefficient $\alpha_{v,s}$ we have the following expressions [7]:

$$\alpha_v = \omega \sqrt{\varepsilon_0 \mu_0 \varepsilon_r} \tan \psi\,, \quad \alpha_s = \frac{R_s}{2\pi Z_{lin}} \left(\frac{1}{r_1} + \frac{1}{r_2} \right), \tag{2}$$

where

$$Z_{lin} = \frac{1}{2\pi} \sqrt{\frac{\mu_0}{\varepsilon_0 \varepsilon_r}} \ln (r_2/r_1) = \frac{60}{\sqrt{\varepsilon_r}} \ln (r_2/r_1)\,, \quad R_s = \sqrt{\frac{\omega \mu_0}{2\sigma}}\,,$$

The applied voltage U is related to the power of the high-frequency wave P by the relation $U = \sqrt{2PZ_{lin}}$.

The processes of heating and melting of the plug are described by the heat-conduction equation [8, 9]

$$\rho c_T \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} r\lambda \frac{\partial T}{\partial r} + \frac{\partial}{\partial z} \lambda \frac{\partial T}{\partial z} + Q (r, z, t)\,, \tag{3}$$

$$Q = \alpha_v W \exp (-\alpha z)\,, \quad W = \frac{P}{2\pi} \frac{1}{\ln (r_2/r_1)} \frac{1}{r^2}\,.$$

Heat release will occur not only in the paraffin-plug volume but also in the steel walls of the coaxial shaft of the well. It is convenient to take into account its influence on the heating of the plug in the boundary conditions on the surfaces of the internal and external pipes.

We will assume that there is no heat exchange on the surface of the internal pipe. Then the boundary condition on this surface has the form

$$-\lambda \left.\frac{\partial T}{\partial r}\right|_{r=r_1} = \frac{1}{r_1^2}\sqrt{\frac{\varepsilon_0\varepsilon_r f}{4\pi\sigma}}\,\frac{P\exp(-\alpha z)}{\ln(r_2/r_1)}\,. \qquad (4)$$

The right-hand side of (4) accounts for the heat release in the wall of the internal pipe.

We assume that the external pipe is in thermal contact with a dry ground [4] and will consider precisely this case. The boundary conditions on the surface of the external pipe can be written in the following form:

$$-\lambda \left.\frac{\partial T}{\partial r}\right|_{r=r_2} = \kappa\,[T(r_2, t, z) - T_0] - \frac{1}{r_2^2}\sqrt{\frac{\varepsilon_0\varepsilon_r f}{4\pi\sigma}}\,\frac{P\exp(-\alpha z)}{\ln(r_2/r_1)}\,. \qquad (5)$$

The first term on the right-hand side accounts for the heat exchange, and the second term accounts for the absorption of the electromagnetic wave on the surface of the external pipe.

At the end of the plug $z = 0$, we specify the boundary condition in the form of convective heat exchange by the Newton law

$$\lambda \left.\frac{\partial T}{\partial z}\right|_{z=0} = \kappa_1\,[T(r, 0, t) - T_0]\,. \qquad (6)$$

We assume that heat exchange is absent at the distant end of the plug $z = H$:

$$\lambda \left.\frac{\partial T}{\partial z}\right|_{z=H} = 0\,. \qquad (7)$$

This condition is fulfilled with a high degree of accuracy for a long plug.

We will assume that the density ρ and the heat conduction of highly paraffinic oil λ are not related to the temperature. The phase transition from the solid state to the liquid state will be taken into account through selection of the following dependence of the heat capacity on the temperature:

$$c_T = c_0 + L\delta\,(T - T_s)\,.$$

Immediately from the heat-conduction equation (3) the energy balance follows:

$$\frac{\partial}{\partial t}\int dV\rho \int_{T_0}^{T} c_T(T')\,dT' = \lambda \oint d\,S\,\mathrm{grad}\,T + \int dVQ\,(T, r, z)\,. \qquad (8)$$

In this case, integration is performed over the entire surface. The left-hand side describes the change in the heat energy stored in the plug in a unit time (heat power). The first term on the right-hand side accounts for the energy loss through the surface of the plug, and the second term describes the power released in the volume of the plug. For the plug in the coaxial shaft of the well Eq. (8) can be transformed to the form

$$\rho\frac{\partial}{\partial t}\int dV \int_{T_0}^{T(r,z,t)} c_T(T')\,dT' = P\,(1 - \exp(-\alpha H)) - 2\pi\kappa_1\int_{r_1}^{r_2} r dr\,[T(r, z = 0, t) - T_0] -$$

$$- 2\pi\kappa r_2 \int_0^H dz\,[T(r = r_2, z, t) - T_0]\,. \tag{9}$$

In the calculations, we used the following thermophysical and electrodynamic parameters of the oil [4, 6]: $\rho = 950$ kg/m^3, $c_0 = 3$ kJ/(kg·K), $T_0 = 20^{\circ}$C, $T_s = 50^{\circ}$C, $L = 300$ kJ/kg, $\lambda = 0.125$ W/(m·K), $\sqrt{\varepsilon_r}\,\tan\psi = 0.032$, $\varepsilon_r = 2.3$, $\kappa = 2.5$ W/(m^2·K) (corresponds to the pipe in dry ground), and $\kappa_1 = 0.2$ W/(m^2·K).

The power of the radiation source P was taken to be equal to 10 kW, the diameter of the external pipe of the coaxial line was 0.1 m, the diameter of the internal pipe was 0.036 m, and the length of the plug was 100 m. The condition σ of the metallic walls was taken to be equal to $\sigma = 4.12 \cdot 10^6$ S/m.

The radiation frequency that determines the value of the coefficient of attenuation of the high-frequency power α must provide the maximum rate and depth of melting of the plug. Indeed, at low α ($\alpha H \ll 1$) practically the entire high-frequency power passes through the plug and only a small part of it is used for heating. At fairly high α ($\alpha H \gg 1$), the main part of the high-frequency power will be absorbed in a narrow layer of the plug material near its boundary adjacent to the high-frequency generator. As a result, we will have the superheating of this region and a strong scattering of energy through the side walls. Thus, there is an optimum value of the coefficient of attenuation of the high-frequency power $\alpha \sim 1/H$ and accordingly of the radiation frequency. In the numerical calculations we used a frequency of 10 MHz, which corresponds to the indicated optimum value of α.

We note that in deriving the expression for the heat-energy source, we made the assumption in the heat-conduction equation that the coefficient of attenuation of the high-frequency power in the plug volume α_v is independent of the temperature. This relation is actually observed for a certain range of frequencies. In particular, at a frequency of 0.1 MHz, $\alpha_v T$ has a pronounced maximum in the vicinity of the phase-transition temperature [4]. As the frequency increases, the position of the maximum shifts to the region of higher temperatures, and the maximum value of α_v decreases. For the selected value of the frequency (10 MHz), the dependence of the attenuation coefficient on the temperature can be neglected with a good accuracy.

For numerical solution of the heat-conduction equation, the explicit difference scheme is used [9]. The delta function was approximated by a step with a width of 0.8°C:

$$\delta_{\epsilon}(x) = \begin{cases} \dfrac{1}{2\epsilon}\,, & -\epsilon < x < \epsilon\,, \\ 0\,, & x < -\epsilon \text{ or } x > \epsilon\,, \end{cases} \qquad \epsilon = 0.4^{\circ}\text{C}\,.$$

Dynamics of Heating and Melting of a Plug in the Shaft of an Oil Well. The numerical calculations were carried out for an initial temperature of the paraffin plug equal to 20°C. The energy balance (9) was used to monitor the accuracy of the numerical calculations. The calculation results are presented in Fig. 2. Figure 2A shows the temperature distributions in the plug volume with regard for the absorption of the high-frequency power and the heat release in the walls of the well shaft, and Fig. 2B shows these distributions without regard for these factors.

A numerical analysis has shown that in the initial period $t < 2$ h (Fig. 2A, a) the temperature distribution in the plug volume is highly nonuniform. The temperature is maximum near the surface of the internal pipe where the heat release is the most intense. Moreover, the temperature decreases with distance from the boundary adjacent to the high-frequency generator to the depth of the plug $z > 0$. This result is evident since the amplitude of the high-frequency wave along the system decreases exponentially. As the temperature approaches the phase-transition point, we have the process of its equalization in the plug volume. Melting (appearance of the liquid phase) begins approximately after 2 h near the surface of the internal pipe. After 6 h, a through channel is melted in the plug.

The surface separating the solid and liquid phases has the shape of a cone with a radius decreasing along the plug. The conical shape of the melted zone can lead to the destruction of the plug to the point of its complete melting. The complete melting of the plug occurs after 34 h. In this case, the maximum temperature of the oil reaches 150°C.

Taking account of the heat release in the walls of the well has a significant influence on the processes of heating and melting of a wax plug. Heating of the steel walls of the well accelerates the process of heating of the plug, which is apparent when Fig. 2A is compared to Fig. 2B. In particular, without regard for the heat release in the

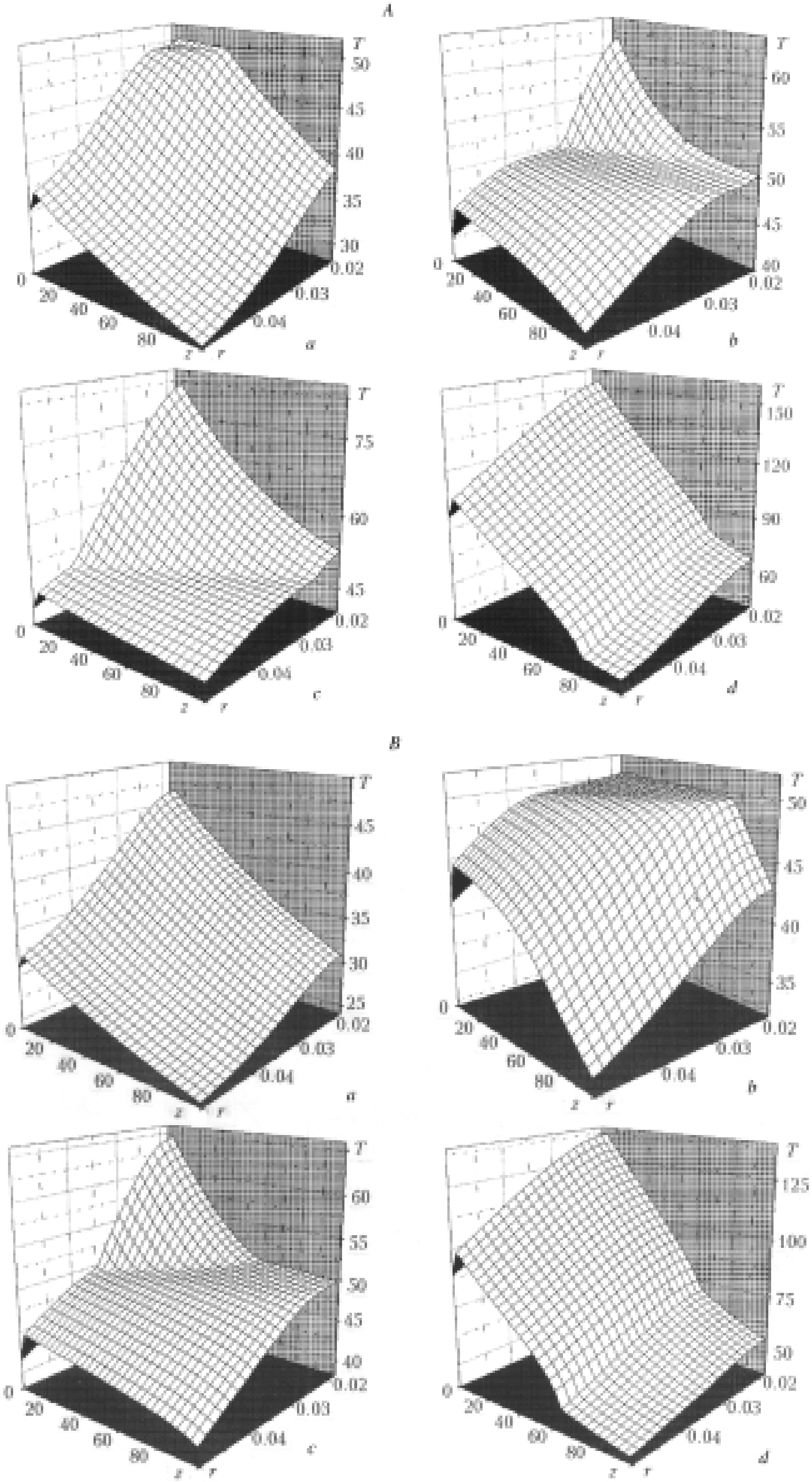

Fig. 2. Temperature profile with (A) and without (B) regard for the heat release in steel pipes for different instants of time in the process of liquidation of an asphalt-paraffin plug of length H = 100 m on the portion of the equipment of an oil well (P = 10 kW, f = 10^7 Hz): A) a) t = 2, b) 6, c) 11, and d) 34 h; B) a) 2, b) 6, c) 11, and d) 50 h.

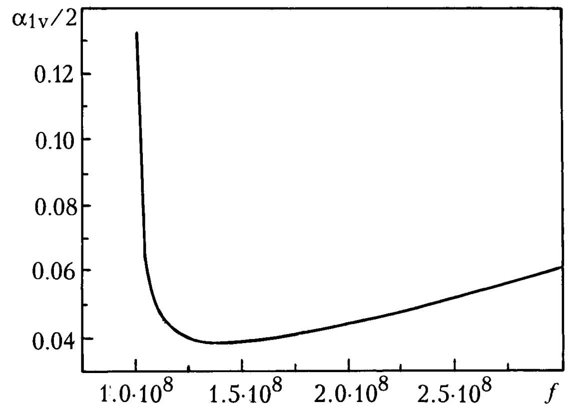

Fig. 3. Dependence of the coefficient of attenuation of the high-frequency field in the volume of a paraffin plug in an oil pipeline on the frequency for the lowest wave of the E type (n = 1). f, Hz.

walls of the well shaft, the time of melting of the through channel in the paraffin plug increased by more than a factor of two — from 6 h to 13.5 h. The time of complete melting of the plug also increased from 34 h to 50 h. The difference between the increase in the rate of melting of the through channel and the increase in the rate of complete melting of the plug in the case where the heat release in the metallic walls is taken into account is explained by the fact that the internal pipe is heated more intensely because of its small radius than the external pipe. This is apparent when expression (4) is compared to expression (5). Therefore, the time of melting of the through channel decreases significantly. At the same time, due to the relatively weak heating of the external pipe, the time of complete removal of the plug increased to a lesser extent (by approximately 40%).

Investigation of High-Frequency Melting of a Paraffin Plug in a Pipeline. From the viewpoint of the high-frequency technique, an oil pipeline is a cylindrical waveguide. We will assume that in the general case the E_{0n} wave with electromagnetic field components is excited in the plug

$$E_z = \frac{1}{2} A J_0\left(\nu_n \frac{r}{R}\right) \exp\,(ik_n z - i\omega t - \alpha_n z/2) + \text{c.s.}\,,$$

$$E_r = -i\frac{A}{2} J_1\left(\nu_n \frac{r}{R}\right)\frac{k_n R}{\mu_n} \exp\,(ik_n z - i\omega t - \alpha_n z/2) + \text{c.s.}\,, \tag{10}$$

$$H_\varphi = -i\frac{A}{2} J_1\left(\nu_n \frac{r}{R}\right)\frac{\omega\varepsilon_0\varepsilon_r R}{\nu_n} \exp\,(ik_n z - i\omega t - \alpha_n z/2) + \text{c.s.}\,,$$

where $k_n = \sqrt{\omega^2\varepsilon_0\varepsilon_r\mu_0 - \nu_n^2/R^2}$,

$$\alpha_n = \alpha_{n\text{v}} + \alpha_{n\text{s}}\,, \quad \alpha_{n\text{v}} = \frac{\omega^2\varepsilon_0\varepsilon_r\,\mu_0}{k_n}\tan\psi\,, \quad \alpha_{n\text{s}} = 2\,\frac{R_\text{s}}{Z_n R}\,, \quad Z_n = \frac{k_n}{\omega\varepsilon_0\varepsilon_r}\,. \tag{11}$$

It follows from the expression for the coefficient of attenuation of the high-frequency power $\alpha_{n\text{v}}$ that it increases significantly as the frequency approaches the cutoff frequency $\omega_{\min} = \nu_n/(R\sqrt{\varepsilon_0\varepsilon_r\mu_0}) \approx 105$ MHz. Figure 3 shows the dependence of $\alpha_{1\text{v}}\sqrt{2}$ (of the coefficient attenuation field) on the frequency for the fundamental wave with parameters n = 1 and ν_1 = 2.405, and the following parameters of the oil pipeline filled with wax: R = 0.72 m, ε_r = 2.3, and $\tan\psi = 1.2\cdot10^{-2}$. It is seen that the attenuation coefficient takes a minimum value at a frequency of 140 MHz and is equal to $\alpha_{1\text{v}} = 4\cdot10^{-2}$ m^{-1}.

For the selected parameters of the pipeline and the plug, the coefficient of attenuation of the electromagnetic field in the steel wall of the pipeline $\alpha_{1\text{s}}/2$ is much lower than the coefficient of volume attenuation in the plug and is inversely proportional to the root of the frequency at high frequencies.

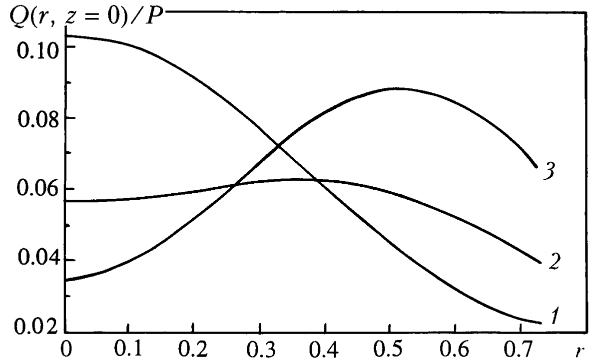

Fig. 4. Transverse distribution of the heat-loss power density normalized to the power source at the point $z = 0$ in a cylindrical waveguide filled with paraffin: 1) $f = 1.4{\cdot}10^8$, 2) $2{\cdot}10^8$, and 3) $3{\cdot}10^8$ Hz.

The processes of heating and melting of a paraffin plug are described by the heat-conduction equation (3) in which the volume-heat-release power for the considered wave of the E_{0n} type can be described by the equation

$$Q = \frac{\tan\psi}{\pi k_n R^4} \frac{\nu_n^2}{J_1^2(\nu_n)} P \exp(-\alpha z) F_n(r), \quad F_n(r) = J_0^2\left(\nu_n \frac{r}{R}\right) + \frac{k_n^2 R^2}{\nu_n^2} J_1^2\left(\nu_n \frac{r}{R}\right).$$

The function $Q(r, z = 0)/P$ characterizes the heat-source-power distribution over the cross section of the wax plug.

Figure 4 shows the dependences $Q(r, z = 0)/P$ for different frequencies of the fundamental wave E_{01}. The main heat release occurs in the near-axis region at comparatively low frequencies (near the cutoff frequency) and at the periphery at high frequencies ($f > 200$ MHz), and its maximum shifts to the wall of the pipe when the frequency increases. On the pipe, the boundary condition for the temperature is analogous to that on the external pipe of the well shaft and has the form

$$\lambda \frac{\partial T}{\partial r}\bigg|_{r=R} = \kappa\,[T(R, z, t) - T_0] - q_s,$$

where

$$q_s = \frac{R_s}{Z_n} \frac{P \exp(-\alpha_n z)}{\pi R^2}.$$

The energy balance for the pipeline can be written in the following form:

$$\rho \frac{\partial}{\partial t} \int dV \int_{T_0}^{T} c(T')\, dT' = P\,(1 - \exp(-\alpha_n H)) - 2\pi\kappa_1 \int_0^R r dr\, [T(r, z = 0) - T_0] -$$

$$- 2\pi\kappa R \int_0^H dz\, [T(R, z, t) - T_0].$$

The processes of heating and melting of a paraffin plug of length 25 m in a steel oil pipeline of radius R = 0.72 m were investigated by numerical methods. The parameters of the high-frequency source were as follows: P = 10 kW and f = 140 MHz. The oil pipeline was in contact with dry ground.

Figure 5A shows the temperature distributions in the volume of the plug at different instants of time. For the indicated frequency, the maximum heat release occurs in the central region of the pipeline. Therefore, the temperature

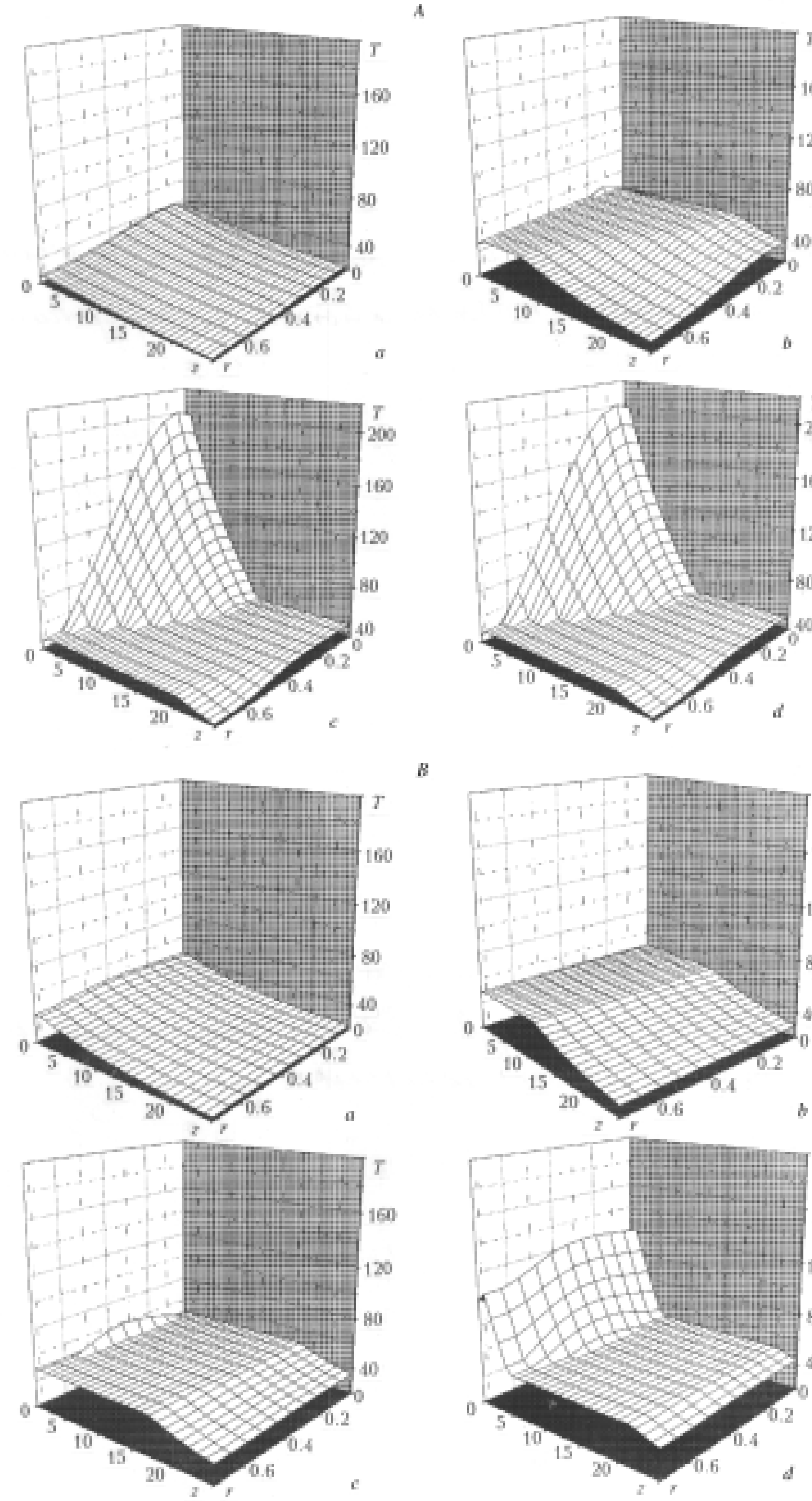

Fig. 5. Temperature profile with (A) and without (B) regard for the heat release in steel pipes for different instants of time in the process of liquidation of a paraffin plug of length H = 25 m on the portion of a pipeline of radius R = 0.72 m (P = 10 kW, $f = 1.4 \cdot 10^8$ Hz): A) a) t = 40, b) 120, c) 200, and d) 300 h; B) a) 40, b) 120, c) 200, and d) 300 h.

is maximum in the neighborhood of the system axis. The temperature distribution is highly nonuniform along the paraffin plug. The temperature decreases rapidly with distance into the depth of the plug. The liquid phase of paraffin appears approximately within 120 h. After 300 h, we are able to melt the plug to a depth of 12 m. It is possible to remove paraffin plugs of comparatively small length from the oil pipelines, which is explained by the strong attenuation (small depth of penetration) of the high-frequency power in the paraffin plug (Fig. 3). Long (longer than 10 m) plugs can efficiently be removal with the use of moving sources of high-frequency power.

As has already been noted, with increase in the operating frequency of the high-frequency generator, the maximum heat release shifts from the near-axis region to the surface of the pipe. In this case, we can obtain a more uniform heating of the plug over its cross section. Figure 5B shows the temperature distributions in the volume of the plug for a frequency of 200 MHz of the high-frequency generator. It is well seen that the temperature distribution over the cross section of the pipe became more uniform and the length of the melted plug decreased. The last-mentioned circumstance is explained by the fact that the depth of penetration of the high-frequency field into the plug decreases as the frequency increases.

CONCLUSIONS

In the work, we have investigated the processes of heating and melting of paraffin plugs in the shafts of oil wells and oil pipelines. The times of melting of a channel in a plug and the times of complete liquidation of the plug have been determined for the selected power and frequencies of the high-frequency source. It has been shown that the process of melting proceeds gradually from the central region of the shaft of a well to the periphery. The conical shape of the melted zone can lead to the destruction of the plug to the point of its complete melting. In the numerical examples considered, a paraffin plug of length 100 m is removed from the coaxial shaft of the well within 34 h. In the oil pipeline, a plug is melted to a depth of 12 m within 300 h, which is practically disadvantageous. It is expedient to decrease the time of melting by increasing the power of the high-frequency generator. The depth of melting of a plug can be significantly increased with the use of a high-frequency radiation source moving in the oil pipeline.

In the present work and in the works of Sayakhov et al. [2–4], the removal of asphalt-paraffin deposits by high-frequency electromagnetic radiation was analyzed for the situation where an asphalt-paraffin deposit fills the entire interior region of a portion of an oil well or an oil pipeline and thus blocks their operation completely. In practice, one tries to prevent such a situation by cleaning asphalt-paraffin deposits from the surfaces of the pipes at the early stage of their formation. Along with traditional methods of removal of asphalt-paraffin deposits partially filling the interior space of a transportation channel, one can use the method proposed by us in the present work for solid wax plugs with small modifications. The high-frequency method is especially efficient for removal of asphalt-paraffin deposits forming a thick film on the inner surface of an oil pipeline [10].

NOTATION

E_r, radial component of the electric field strength, V/m; H_φ, azimuth component of the magnetic field strength; φ, angular coordinate; U, high-frequency voltage applied across the electrodes of the coaxial line, V; ω, circular frequency, rad/sec; f, electromagnetic-radiation frequency, Hz; k, longitudinal wavenumber in the dielectric coaxial line, 1/m; r, running radius, m; ε_0, electric constant of vacuum, F/m; μ_0, magnetic constant of vacuum, H/m; ε_r, relative permittivity of highly paraffinic oil; $r_{1,2}$, radii of the external and internal pipes, m; α, total coefficient of attenuation of the high-frequency power, 1/m; α_v, coefficient of attenuation of the high-frequency power in the volume of a plug, 1/m; α_s, coefficient of attenuation of the high-frequency power in the walls of the coaxial line, 1/m; tan ψ, dissipation factor (dielectric loss tangent); Z_{lin}, linear impedance of the coaxial line, Ω/m; R_s, surface resistance, Ω/m; Z_n, characteristic resistance of the transmission line, Ω/m; σ, conductivity of the pipeline walls, S/m; P, electromagnetic-radiation power, W; Q, power density of the volume heat release, J/m^3; T, temperature, K; T', corresponds to the temperature T in the integrals for the adequacy of mathematical representation, K; ρ, density of the oil, kg/m^3; c_T, heat capacity of the oil with account for the phase transition, J/(kg·K); c_0, heat capacity of the paraffin (oil) before and after the phase transition, J/(kg·K); L, latent heat of the phase transition, J/kg; T_s, temperature of the phase transition, K; T_0, ambient temperature, K; λ, thermal conductivity of the oil, W/(m·K); κ, heat-transfer coefficient, W/(m·K); κ_1, heat-transfer coefficient at the front end of a plug, W/(m^2·K); $\delta(x)$, delta function; dV, element of the plug volume, m^3; dS, element of the plug surface, m^2; H, length of the plug, m; t, time, sec; E_z, longitudinal component of the electric field strength, V/m; z, longitudinal coordinate, m; k_n, longitudinal wave number of the nth radial harmonic, 1/m; n, integral number; R, radius of the oil pipe, m; $J_0(\nu_n)$, Bessel function of the first kind; ν_n, root of the Bessel function of the first kind; ν_1, first root of the Bessel function of the first kind; A, amplitude of the electric field strength, V/m; $\alpha_{n\mathrm{v}}$, coefficient of attenuation of the high-frequency power in the volume of a cylindrical plug, 1/m; $\alpha_{n\mathrm{s}}$, coefficient of attenuation of the high-frequency power in the wall of a cylindrical waveguide, 1/m; $\omega_{\min}$, cut-off frequency of a circular waveguide, rad/sec. Subscripts: r, relative; v, volume; s, surface.

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