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NUMERICAL MODELING OF HIGH-FREQUENCY ELECTROMAGNETIC HEATING OF A DIELECTRIC PLUG CLOGGING A PIPE

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The formation of plugs in pipelines and well shafts caused by deposition of paraffins, resins, or gas hydrates often complicates oil and gas production. In the process of exploitation of wells, asphalt-resin-paraffin deposits are formed on the surfaces of tubing strings as a result of decreases in temperature and pressure. In some cases, they completely clog the space between pipes, which stops production from a well. The results of laboratory investigations and industrial tests show that one promising method of controling the formation of plugs is the use of high-frequency electromagnetic heating [1–3].

From the point of view of radio engineering, the internal space of a well equipped with a tubing string is a coaxial transmission line along which electromagnetic radiation with a frequency of up to $\sim 10^{10}$ Hz (the frequency is not limited from below) and power $P \sim$ 10–20 kW can be directed. Meeting a plug, the electromagnetic radiation heats it to the melting point or decomposition temperature and thereby eliminates the obstacle. The advantages of this heating method over the usual methods (hot water, electric heater, etc.) are, first, volume heating of the plug (owing to deep penetration of the electromagnetic radiation), i.e., heating is much more rapid and uniform in volume, and, second, the absence of a heat-transfer agent, which makes control of the heating process easy and adaptable.

In order to achieve maximum effectiveness (in velocity and maximum depth of melting), it is necessary to choose correctly the radiation frequency, which determines the absorption factor α and the related depth of electromagnetic radiation penetration $l = 1/\alpha$. If the factor α is too small (a very great depth of penetration l), a considerable part of radiation power goes through the plug or is distributed over a great length and is dissipated through the pipe walls without providing the required heating. When the factor α is too large (a very small depth l), a large amount of the power is absorbed in the layers of the plug substance that are the nearest to the radiator. This causes overheating of the layers and intense energy dissipation through the corresponding sections of the lateral wall. In both cases, heating is not effective, and the depth of melting is small. Consequently, there are optimum values of α for which the greatest depth and rate of melting are achieved (for given plug dimensions and conditions of heat exchange). Finding of these optimum values is the aim of the paper.

In addition, for some substances in a certain frequency range the factor α depends significantly (in a resonant way) on temperature, and this can be used to increase the effectiveness of heating. If the radiation frequency is chosen correctly, heating can be realized in the "thermal wave" regime, and its rate can be substantially increased. Moreover, using the nonlinear function $\alpha(T)$, we can obtain a temperature wave moving in the opposite direction: from the remote end of the plug to the radiation source, i.e., an effect which is impossible under normal conditions. These processes have also been modeled in this work.

Model and System of Equations. Numerical investigations were carried out using a two-dimensional axisymmetric model. The space between two coaxial circular metal pipes (R is the radius of the outer pipe and R_1 is the radius of the inner pipe) is clogged by a dielectric plug of length H consisting, for example, of solidified high-paraffin oil. At time $t = 0$, a source is brought into operation, which creates an electromagnetic

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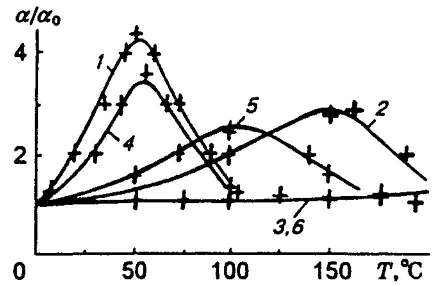

Fig. 1

radiation flux propagating along this coaxial line. Owing to radiation absorption, volume heating and melting of the dielectric take place. The heat exchange with the environment on the surface of the outer pipe follows Newton's law with a given coefficient of heat exchange æ. The absorption factor α of electromagnetic radiation depends on the radiation frequency and, in some frequency range, on the temperature of the medium.

The process of heating is described by the equation of thermal conductivity:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{r \partial r}\left(\lambda r \frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) + Q(z,t).$$

Here Q is the power density of volume heat release:

$$Q = W\alpha(T)\exp\left\{-\int_0^z \alpha(T)\,dz\right\}; \tag{1}$$

$$W = P/[\pi(R^2 - R_1^2)]. \tag{2}$$

Formula (2) assumes a uniform distribution of power over a circular cross-section of the interpipe space. In the case of an ideal coaxial line, the power density is somewhat higher near the inner conductor than near the outer conductor. However, in real situations, since the conductors are not exactly coaxial and small inhomogeneities are present in the material of the plug, field distortion and wave scattering occur, which cause equalization of the power density over the cross-section.

If the absorption factor α can be considered independent of temperature, formula (1) becomes the Bouguer–Lambert absorption law: $Q = W\alpha\exp(-\alpha z)$. The boundary condition at the surface of the outer pipe has the form

$$-\lambda \left.\frac{\partial T}{\partial r}\right|_{r=R} = æ(T(R,t) - T_0)$$

(T_0 is the temperature of the environment).

The condition of the absence of heat exchange is specified at the surface of the inner pipe:

$$-\lambda \left.\frac{\partial T}{\partial r}\right|_{r=R_1} = 0.$$

The thermal conductivity λ and the density ρ are considered constant and independent of temperature, and the heat capacity c has the following singularity at the phase transition temperature T_s: $c(T) = c_0 + L\delta(T - T_s)$. Here L is the latent heat of phase transition and δ is a delta function, which is replaced in the numerical modeling by a "step" of finite width.

The absorption factor of electromagnetic radiation in the dielectric is computed, in accordance with [4], by the formula

$$\alpha = \frac{2\pi f}{C_R}\sqrt{\varepsilon}\tan\delta,$$

where f is the radiation frequency; C_R is the velocity of light in vacuum; ε is the dielectric permeability; and $\tan\delta$ is the dielectric loss tangent.

TABLE 1

Nu	β
1.0	0.15...3.5
10.0	0.35...2.1
∞	0.65...1.6

The frequency and temperature dependences of ε and $\tan\delta$ for different materials in oil technology are given in [5, 6]. Experiments show that the dependence $\alpha(f)$ at fixed temperature can be considered with good accuracy a linear function, and a typical form of the dependences $\alpha(T)$ at some fixed frequencies is shown in Fig. 1, where curves 1–3 represent bituminous oils at frequencies of 10^5, $5 \cdot 10^6$, and 10^8 Hz, and curves 4–6 represent high-paraffin oils at the same frequencies. To satisfy the scale of the picture, all the curves are normalized to the corresponding absorption factor α_0 at $T = 0$. It is seen that increased absorption (of resonant form) is observed in some frequency range, due to an abrupt change in the viscosity of oils in this temperature range and the associated decrease in the relaxation time of dipole molecules (resins, asphaltenes, etc.). With increasing frequency, the absorption maximum decreases in amplitude and is shifted to higher temperatures, and for a fairly high frequency, the absorption factor is practically independent of temperature. Thus, by varying the radiation frequency, both the absolute value of the factor α and the character of its temperature dependence can be changed.

The radiation absorption in the pipe walls was not taken into account. Experimental investigations [7] of materials that are usually used in pipes for the oil and gas industries show that, at frequencies of up to 10^8 Hz, losses in the pipe walls do not exceed 10–20% of the source power per 100 m of pipe length. These losses do not cause fundamental changes in the pattern of plug heating and can be compensated by a corresponding increase in the power of the source.

The algorithm of numerical modeling is described in [8, 9]. The rounded thermophysical parameters of high-paraffin oil were used in the calculations: $\rho = 950$ kg/m, $c_0 = 3$ kJ/(kg · K), $T_s = 50°$C, $L = 300$ kJ/kg, $\lambda = 0.125$ W/(m · K), and $\sqrt{\varepsilon}\tan\delta = 0.03$.

The power P of the radiation source was 10 kW, the diameter of the outer pipe $2R = 0.1$ m, and that of the inner pipe $2R_1 = 0.036$ m.

Results and Discussion. The results of modeling for α that does not depend on temperature, i.e., when the frequency f is sufficiently high, are given in Figs. 2–4 and in Table 1.

Figure 2 presents the dimensionless time of the complete melting of a plug $\tau = \lambda t/(c_0 \rho H^2)$ as a function of the dimensionless absorption factor $\beta = \alpha H$ under different conditions of heat exchange on the surface of the outer pipe, which are determined by the Nusselt number $\mathrm{Nu} = \text{æ} R/\lambda$. Curve 1 corresponds to Nu = 0 (a thermaly insulated pipe), curve 2 to Nu = 1 (a pipe in dry ground), curve 3 to Nu = 10 (a pipe in wet ground), and curve 4 to Nu = ∞. From Fig. 2 one can see how important correct choice of the absorption factor α is. For its optimum value ($\alpha = 1/H$), which corresponds to frequency $f \approx 1.6 \cdot 10^7$ Hz for a 100-meter plug, the melting time is 15–30 h (depending on the conditions of heat exchange) but can be an order of magnitude higher, if the value of α differs from the optimum value by a factor of 2 or 3. Moreover, for Nu $\neq 0$ (as is seen from Table 1) there is an interval of values of β outside which complete melting cannot be achieved at all. This interval is the narrowest in the most unfavorable case (Nu = ∞), i.e., when a constant ambient temperature T_0 is maintained on the surface of the outer pipe. For Nu = 0, melting is achieved, certainly, for any $\beta \neq 0$, but in this case, too, the melting time has a clear minimum at $\beta = 1.0$.

It should be noted that the optimum frequency for the heating of a rather long plug (~10–20 MHz) is more than an order of magnitude lower than the optimum frequency for the heating of an oil pool (~300 MHz, as shown in [8, 9]). This is explained by the fact that the optimum frequency in volume electromagnetic heating corresponds to a depth of radiation penetration that is approximately equal to the dimensions of the object

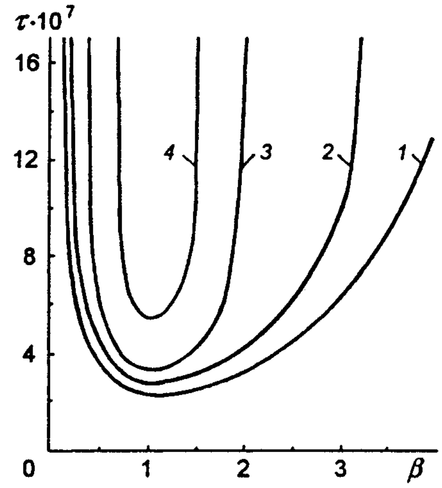

Fig. 2

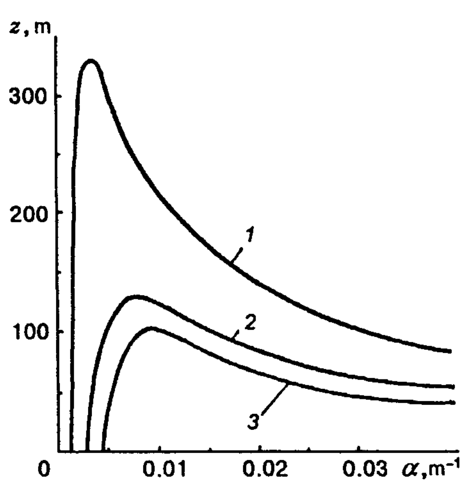

Fig. 3

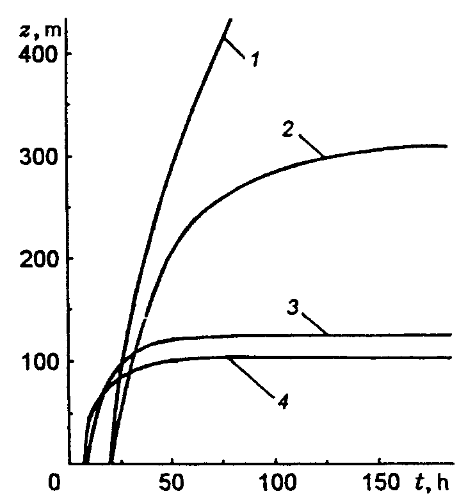

Fig. 4

being heated in the direction of radiation propagation. The radius of heating of a pool (for a reasonable source power of several tens of kilowatt) does not exceed 10 m, and the plug length in a well is usually greater than 100 m. In this case, the volume of the plug being heated is two orders of magnitude smaller and, correspondingly, the heating time is measured in hours, whereas the time of pool heating (with comparable powers) is measured in tens of days. Thus, the requirements for the equipment used in the electromagnetic heating of a pool and for the equipment used for the elimination of plugs in wells differ substantially.

If the length of the plug is not known in advance, it is of interest to answer to the following questions: What is the maximum depth of melting that can be achieved in the heating of an "endless" plug (i.e., if $H \gg 1/\alpha$) by a radiator with a given power, and what must the absorption factor be? The results of modeling of the heating process for this case are presented in Figs. 3 and 4.

Figure 3 shows the maximum depth of melting z as a function of the absorption factor (curves 1–3 for Nu = 1, 10, and ∞), and Fig. 4 shows the dynamics of melting front propagation for the corresponding optimum values of the factor α (the curves 1–4 for Nu = 0, 1, 10, and ∞). From Fig. 3 it is possible to

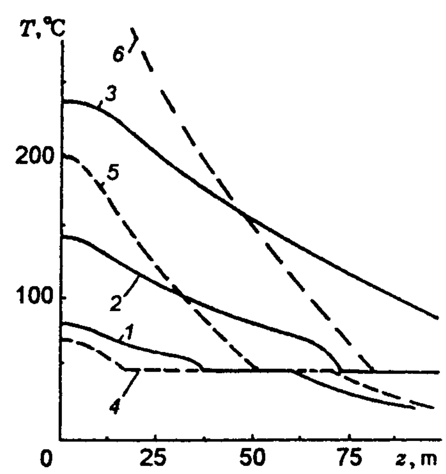

Fig. 5

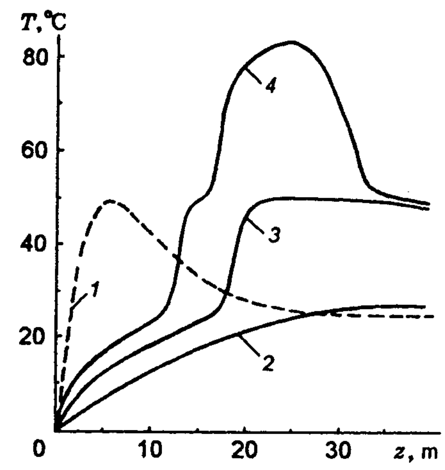

Fig. 6

determine the optimum value of α at which the maximum depth of melting is reached, and from Fig. 4 one can determine the time required for a stationary temperature field to be established in the model under consideration, i.e., the maximum heating time after which the calculations make no practical sense. With correct choice of α (as is evident from these figures), melting of up to ~150–300 m can be achieved in a quite reasonable time even with intense heat exchange on the surface of the pipe. When Nu = 0, the depth of melting is not limited, and, therefore, there is neither an optimum (in terms of the maximum depth) value of α nor the time at which a stationary temperature field is attained.

Figures 5 and 6 give the results of modeling of heating when the dependence $\alpha(T)$ has the form shown in Fig. 1 (curve 4). In this case, intense absorption of electromagnetic energy takes place only in a temperature interval near T_s, and the regions that are heated more strongly or more weakly have a substantially smaller absorption factor α, i.e., they are transparent to this frequency. In this heating regime, a narrow absorbing area surrounding the melting front moves in the medium as a temperature wave.

Figure 5 presents temperature-field profiles in a plug of length $H = 100$ m at 2.5, 5, and 10 h after the beginning of heating (curves 1–3, correspondingly). For comparison, field profiles for the same times (curves 4–6) are shown for heating in which the factor α does not depend on temperature and ensures the same integral absorption of energy in the entire plug. It is seen from the figure that the temperature gradient near the melting front for curves 1–3 is substantially greater than for curves 4–6, which ensures a greater front propagation velocity. At the same time, overheating of the upper part of the plug near the source is considerably smaller for curves 1–3, which gives a noticeable gain in energy. Figure 6 shows the process of heating of a plug by a reverse temperature wave, i.e., by a wave moving from the remote end of the plug to the radiation source. The length of the plug is 40 m and Nu = 0. To realize this regime heating, it is necessary to create a reverse temperature gradient, i.e., a gradient that is directed from the radiation source to the remote end of the plug. This can be done, for example, in the following way. First, the plug is heated to a temperature of not higher than T_s (curve 1, $\alpha = 2.5 \cdot 10^{-3}$ m^{-1}, $t = 6$ h). Then the radiation source is turned off and the near end of the plug is cooled by a cold air flow until a monotone temperature profile increasing with z is obtained (curve 2). After this, the radiation source is turned on again at a frequency corresponding to the resonant absorption at temperature T_s. In this case, the radiation passes through the weakly heated layers of the plug material and is absorbed at the warmer, remote end. This leads to quick heating of remote layers, which causes more effective absorption of radiation, and the quick attainment of temperature T_s at the remote end (curve 3, 75 minutes after repeat heating). The plug begins to fail from the remote end, simultaneously heating the layers adjacent to the melting front on the source side; the heated layers absorb radiation, and a temperature wave arises which moves to the origin of the z axis (curve 4, 150 minutes after repeat). Such an unusual heating regime, which is possible only with nonlinear volume heat release, can be useful and effective in various cases. For example, when a gas hydrate plug is destroyed from the remote end, one can create an excess pressure behind the plug that will push out the plug before it is completely destroyed by heating. And this will reduce the heating time and the consumption of energy. Using this method very large plugs could be destroyed by stages, by creating heated zones at a distance of 50–100 m from the radiation source.

Thus, a numerical investigation of the process of electromagnetic heating of a plug consisting of solidified oil products in a well was carried out using a two-dimensional axisymmetric model for various conditions of heat exchange at the outer surface of the pipe. The optimum value of the absorption factor α, which depends on the frequency of electromagnetic radiation, time, and maximum possible melting depth of a plug, as well as values of α at which complete melting of a plug of a given length is possible are determined. The optimum frequency for the heating of a plug with a length of ~100 m or more is in the range of 10–20 MHz, which is more than an order of magnitude lower than the optimum frequency for the heating of an oil pool. The heating regimes at frequencies at which increased absorption (of a resonant type) occurs in the temperature range of 40–60°C were modeled. It was shown that heating in this case can be realized in the regime of a "thermal wave" and that it is possible to obtain a nonmonotone temperature distribution and thermal destruction of the plug from the end remote from the source.

The physical parameters characteristic of an oil with a high paraffin content were used in the modeling. It was established that with optimum heating parameters using a source with a power of 10 kW, a plug with a length of 100–200 m in a pipe with a diameter of ~0.1 m can be destroyed in ~15–30 h. These results seem to be quite acceptable from a practical point of view, and the method of electromagnetic heating appears to be technically feasible and competitive in comparison with the conventional methods of heating (by a hot liquid, vapor, electric heaters, etc.)

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