TABLE 2

Parameter	Equation	α		
		10^{-1}	10^{-2}	10^{-3}
y_{max}	(2.14)	4,000	10,40	30,82
	(2.15)	4,056	10.45	30,82
τ_*	(2.14)	3,375	11,65	38,32
	(2.15)	3,631	12,00	38,48

For change in α from $5\cdot10^{-2}$ to $5\cdot10^{-4}$ the velocity reestablishment coefficient for the collision $\varepsilon = -V(\tau_c)$ decreases from 0.993 to 0.554, i.e., within the limits of values typical of laboratory pile driver collision experiments [2, 4].

We will note that the results of the ε calculations should not be overrated, since they were obtained, first, within the framework of a linearized model of wave disturbances, and second, under conditions difficult to obtain in practice (plane-parallel approach of bar and striker faces, absence of wave dispersion, etc.). Moreover, the assumption of an absolutely rigid striker eliminates dependence of ε on the material of the colliding bodies.

Thus, the above analysis of wave and quasistatic descriptions of the process of longitudinal collision of elastic bodies has shown that at small ratios of bar/striker mass both approaches yield similar results as regards maximum stresses and collision times, which agree well with data from the literature. The values found for the velocity reestablishment coefficient upon collision do not contradict experimental values.

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NUMERICAL MODELING OF PETROLEUM HEATING AND FILTRATION IN A PLATE UNDER THE ACTION OF HIGH-FREQUENCY ELECTROMAGNETIC RADIATION

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UDC 532.546:536.421

The use of high-frequency electromagnetic radiation is a promising method for intensifying production of high viscosity petroleum. Because of its deep penetration and consequent volume heat liberation, electromagnetic radiation enables a much higher and more uniform heating rate and a higher efficiency than the traditional thermal methods of heated vapor or hot liquid. However, realization of such capabilities requires detailed study of the heat-mass transport processes which occur, in order to discover optimal operating regimes. Estimates of penetration depth, temperature distribution, and filtration rate in one-dimensional models were made in [1-4]. A two-dimensional plate model was studied in [5], but without consideration of petroleum filtration (plate heating with closed well). At the same time it is possible (and field tests have been carried out [6]) to heat a plate electromagnetically while simultaneously extracting oil, to model which consideration of both heat transport and petroleum filtration in the porous plate are obviously necessary. Determination of optimum parameters in such a regime is the goal of the present study.

Model and Equations. Numerical studies were performed with a two-dimensional axisymmetric model, a diagram of which is shown in Fig. 1. The petroleum stratum is contained

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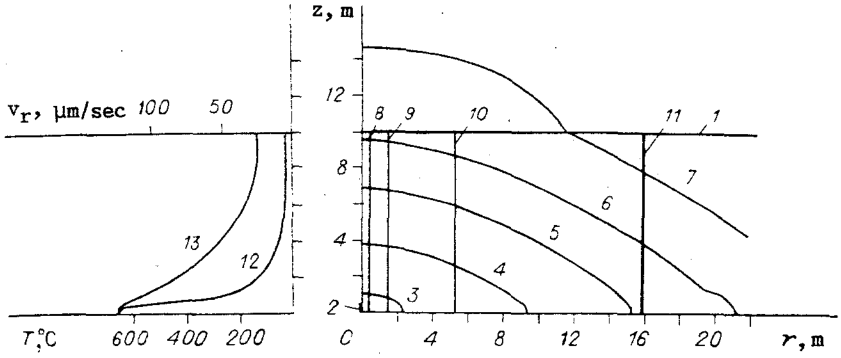

Fig. 1

between planes perpendicular to the z-axis (line 1). The model is symmetric about the plane z = 0, so that only the upper half is shown. The plate is bounded above and below by an infinite medium, the physical characteristics of which (thermal conductivity, density, heat capacity) differ from those of the plate. An electromagnetic radiation source 2 with power of tens to hundreds of kW is placed in the well. Electromagnetic waves propagate in a radial direction about the well; they are absorbed and volume heating of the plate and adjacent rock occurs. Because of the heating the viscosity of the oil decreases and its flow into the well increases.

For fixed dimensions and source power the size of the heated zone depends on the physical parameters of the medium and the electromagnetic wave penetration depth. This depth, in turn, depends on the frequency of the radiation and can thus be controlled. For too great penetration depths (too low a frequency) the source energy is dissipated in a large region and leaks into the adjacent rock without producing the required heating. For too small a penetration depth (too high a frequency) intense heating of a small region surrounding the source occurs, a high temperature gradient develops, and heat is lost intensely upward and downward without providing the required radial heating. In both cases the heated zone is small and heating is ineffective. Consequently, there must exist some optimum frequency at which (for fixed source power) the most effective heating can be produced. For the same reasons there exists an optimum size (height) for the radiator located in the well. As for source power, within the framework of the model used, the higher that power, the higher the well yield, but also the higher the heat loss. Therefore the efficiency of heating (ratio of the increase in petroleum yield to energy expended) can prove low for too high a power level. Moreover, the radiated power is limited by the fact that it is undesirable to heat the oil above the temperature at which it decomposes. Determination of optimum values for radiation frequency and radiator size and power is the basic task of our numerical modeling.

Within the framework of the model chosen the process of heating and filtration is described by a system of interrelated equations of thermal and piezoconductivity:

$$\rho c\frac{\partial T}{\partial t}+m\rho_1 c_1\left(v_r\frac{\partial T}{\partial r}+v_z\frac{\partial T}{\partial z}\right)=\frac{1}{r}\frac{\partial}{\partial r}\left(\lambda r\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+ \quad (1)$$

$$+\frac{\alpha W\psi(z)}{2\pi rh}\exp\left[-\alpha(r-b)\right],\quad b\leqslant r<\infty,\ -\infty<z<\infty;$$

$$\frac{\partial p}{\partial t}=\frac{k}{m\beta_p}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{r}{\mu}\frac{\partial p}{\partial r}\right)+\frac{\partial}{\partial z}\left(\frac{1}{\mu}\frac{\partial p}{\partial z}\right)\right]+\frac{\beta_T}{\beta_p}\frac{\partial T}{\partial t},\quad b\leqslant r<\infty,\quad -H/2\leqslant z\leqslant H/2. \quad (2)$$

Here ρ, c, λ are the density, heat capacity, and thermal conductivity of the medium, averaged over all phases (these quantities are different in the plate and adjacent rock, and are thus functions of z); ρ_1, c_1, μ are the density, heat capacity, and viscosity of the filtering liquid (petroleum); m is the porosity coefficient; v_r, v_z are the components of the filtration velocity vector; α is the electromagnetic radiation absorption coefficient; W, h are the power and height of the radiation source; b is the well radius; k is the permeability coefficient; $\beta_p = (\partial\rho_1/\partial_p)/\rho_1$ is the compressibility coefficient; $\beta_T = -(\partial\rho_1/\partial T)/\rho_1$ is the thermal expansion coefficient of the filtering liquid; H is the plate height; and ψ(z) is a function characterizing the distribution of absorbed radiation power over height. For a radiator with an ideal directional pattern (which we will consider here) we can write the function ψ(z) in the form

$$\psi(z)=\begin{cases}1 & \text{for}\quad -h/2\leqslant z\leqslant h/2,\\ 0 & \text{for}\quad z<-h/2,\quad z>h/2.\end{cases}$$

TABLE 1

H, m	p_0, MPa	T, °C	k, D	m	ρ_1, kg/m^3	$\rho_1 c_1$, kJ/(m^3·K)	λ, W/(m·K)	β_p, Pa^{-1}	β_T, K^{-1}	μ_0, MPa·sec	ε	tg δ
20	8	20	1,5	0,32	940	2310	1,0	$2{,}7\cdot 10^{-10}$	$5\cdot 10^{-4}$	550	2,60	0,02

Equations (1) and (2) are interrelated in that Eq. (1) considers convective heat exchange, which is dependent on pressure (Darcy's law):

$$v_r = -\frac{k}{\mu}\frac{\partial p}{\partial r}, \quad v_z = -\frac{k}{\mu}\frac{\partial p}{\partial z}, \tag{3}$$

while Eq. (2) considers the dependence of the oil viscosity on temperature and its volume expansion due to heating. Natural convection in the gravitational field cannot develop under the given conditions, since the Rayleigh number

$$\mathrm{Ra} = g\frac{\beta_T \rho_1 \rho_1 c_1 k}{\mu\lambda}\Delta T H \ll 1$$

for any reasonable temperature head ΔT.

Initial and boundary conditions are as follows:

$$T|_{t=0} = T_0, \quad \left.\frac{\partial T}{\partial r}\right|_{r=b} = \left.\frac{\partial T}{\partial r}\right|_{r\to\infty} = \left.\frac{\partial T}{\partial z}\right|_{z\to\pm\infty} = 0; \tag{4}$$

$$p|_{t=0} = p_0, \quad p|_{r=b} = p_b, \quad p|_{r\to\infty} \to p_0, \quad \left.\frac{\partial p}{\partial z}\right|_{z=\pm H/2} = 0 \tag{5}$$

(T_0, p_0 are the initial intraplate temperature and pressure, p_b is the pressure in the well).

Solution Method. After transforming to dimensionless notation (in a manner similar to [5]) a locally one-dimensional scheme on a nonuniform grid was used [7, 8]. In each time step an iteration process following this algorithm was used: solve Eq. (1) with v_r, v_z taken from the previous step; 2) solve Eq. (2) with new temperature values, then use Eq. (3) to find new values of v_r and v_z; 3) solve Eq. (1) with the new v_r, v_z values and compare the results to that obtained in the previous iteration. If agreement is lacking (within the specified accuracy), solve Eq. (2) again, etc. The length of the step in time was automatically regulated by the speed with which the iteration process converged.

The program was written in the Fortran language and modeling carried out on an ES 1045 computer. The grid size was 50 × 50 with increasing step size with removal from the source along both coordinates.

Object of Study. Physical parameters characteristic of the Russian Tyumen' field, published in [9-11], were used in the modeling. The more significant values are presented in Table 1.

Deviations from a linear filtration law are insignificant for Russian petroleum [9, 11]; the temperature dependence of viscosity can be approximated well by a generalized Andrade expression

$$\mu(T) = \mu_\infty \exp\{E_\mu/[R(T - T_s)]\},$$

where E_μ is the activation energy; T_s is the temperature of complete solidification; μ_∞ is the viscosity limit as $T \to \infty$; R is the universal gas constant.

The index of electromagnetic radiation absorption was calculated after [12] with the expression

$$\alpha = \frac{2\pi f}{C_R}\sqrt{\varepsilon}\,\mathrm{tg}\,\delta.$$

Here f is the radiation frequency; C_R is the speed of light in vacuo; ε is the dielectric permittivity; $\tan\delta$ is the dielectric loss angle.

Results and Evaluation. The results of the modeling are presented in Figs. 1-6 in dimensional form for convenience.

Figure 1, which was used above to describe the model, shows isotherms and isobars of the steady-state temperature and pressure fields in the plate, as well as the temperature distribution and filtration rate at the well surface for a radiated power W = 100 kW, f = 400 MHz,

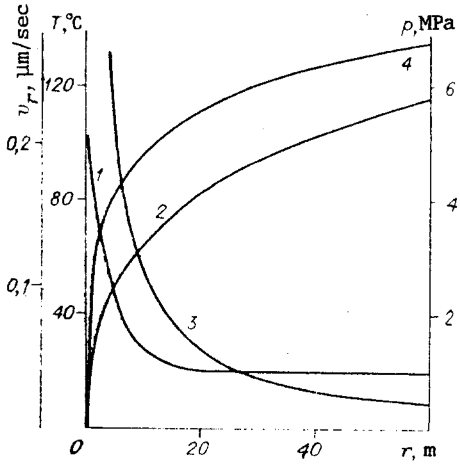

Fig. 2

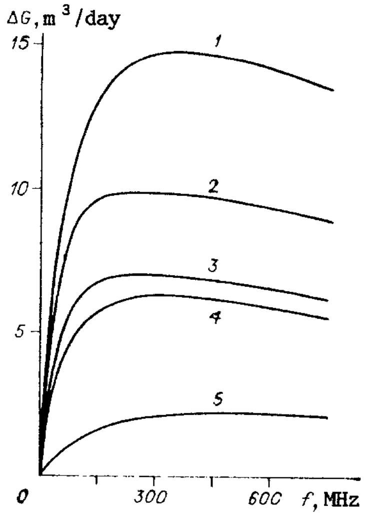

Fig. 3

h = 1.0 m. Curves 3-7 show isotherms with temperatures of 250, 50, 25, 21, 20.1°C, while curves 8-11 are isobars with pressures of 1, 2, 3, 4 MPa, and curves 12, 13 are profiles of temperature and filtration rate at the well surface, respectively.

Because the piezoconductivity coefficient $\varkappa_0$ is much greater than the thermal diffusivity coefficient a_0, the pressure in the plate is established significantly more rapidly than the temperature, and because of boundary conditions (5) (impermeable plate boundaries at $z = \pm H/2$) the isobars are practically cylindrical surfaces. Therefore, the velocity $v_z \approx 0$ over the extent of the entire heating process, which significantly eases the modeling by increasing the speed of convergence of the iteration process. However, the problem cannot be reduced to one dimension, because of the strong dependence of viscosity on temperature, and hence, z-coordinate.

Figure 2 shows profiles of steady-state temperature and pressure fields, as well as the filtration rate profile in the plate in the radial direction, for W = 100 kW, f = 300 MHz, h = 20 m. Curve 1 is the temperature profile, curve 2 the pressure profile, curve 3 the filtration rate, curve 4 the steady-state pressure profile which would be established in the absence of heating. From the filtration rate we can estimate the local Peclet number $Pe = v_r/(a_0\alpha)$, where for the characteristic dimension we take the radiation penetration depth $1/\alpha$. From Fig. 2 we easily find that $Pe \sim 1$ at a distance $r \sim 10$ m from the well. Thus, from the viewpoint of the character of heat transport we can distinguish two regions: close to the well, where convective heat transport predominates ($Pe > 1$), and the far zone, where conventional heat transport predominates ($Pe < 1$). In the absence of heating, because of the high viscosity of the petroleum near the well, a high pressure gradient is established (curve 4). Heating reduces the viscosity, and the pressure gradient undergoes significant equalization (curve 2), as a result of which the depression radius (marked pressure reduction) comprises tens of meters, i.e., several times greater than the heating radius, which is equal to 15-20 m (line 1).

From a practical viewpoint the most important result of heating is the increase in well output $\Delta G = G - G_0$ as compared to the output of the "cold" well $G_0 \approx 10$ m³/day.

Figure 3 shows the increase in well output due to electromagnetic heating as a function of radiation frequency for various radiator sizes h and powers W (lines 1-5 correspond to W = 100, 100, 150, 100, 10 kW, h = 0.4, 1, 20, 20, 10 m). All the lines have more or less clearly expressed maxima at frequencies from 200 to 500 MHz, while for reduction in frequency below 100 MHz the efficiency of heating decreases abruptly. The physical meaning of these maxima was discussed above. A more precise value of the optimum frequency depends on the size and power of the radiator. We will note that for decrease in power the maximum of the curve (i.e., the most effective frequency) shifts toward higher values, which is quite natural, since at low power values, it is more desirable to concentrate a greater part of that power near the well, i.e., to increase the absorption coefficient α.

Figure 4 shows the dependence of increase in well output on radiated power for various radiator dimensions h and a frequency of 300 MHz, which is close to optimum for a wide range of source W and h (see Fig. 3). Curves 1-6 correspond to h = 0.4, 0.2, 1, 5, 10, 20 m. With

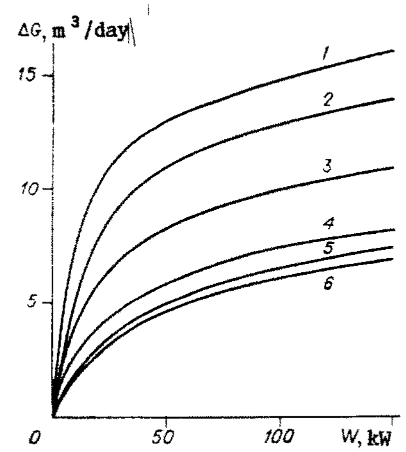

Fig. 4

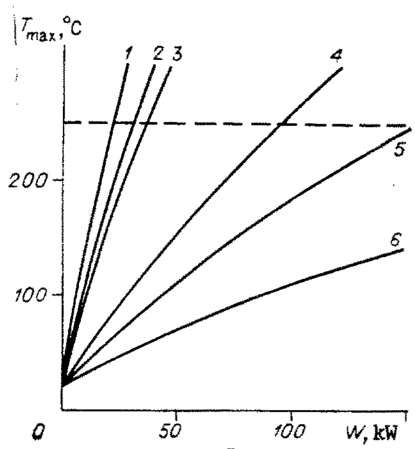

Fig. 5

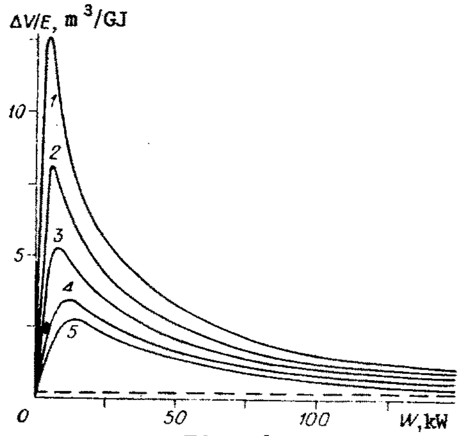

Fig. 6

increase in power the increase in output naturally increases, although heat losses also increase, the latter being especially large for large radiator dimensions. If radiator dimensions are too small, intense overheating of a region adjacent to the radiator occurs, which also leads to additional energy loss. As is evident from Fig. 4, the greatest increase in well output is achieved at h = 0.4 m; this size is then optimal. Correct choice of radiator size is no less important than correct choice of frequency. For example, a radiator with W = 30 kW of optimal size 0.4 m yields almost twice the heating effect of a radiator with W = 150 kW, h = 20 m.

Figure 5 shows the dependence of maximum petroleum temperature (temperature at the level of the middle of the radiator z = 0) on radiated power for f = 300 MHz. Curves 1-6 correspond to h = 0.2, 0.4, 1, 5, 10, 20 m, while the dashed line is the temperature at which the petroleum begins to decompose, $T_* = 250°C$. The smaller the radiator size for a given power, the larger the energy flux density and the more intense the heating of the near zone adjacent to the radiator. Therefore for small radiator size there is an upper limit on power of several tens of kW. In particular, for a radiator with h = 0.4 m the power should not exceed 30 kW.

Figure 6 shows the dependence of heating efficiency on radiated power. Efficiency is defined here as the ratio of the excess petroleum extracted (due to heating) over the course of a day ΔV to the energy E used over that period. Curves 1-5 correspond to h = 0.4, 0.2, 1, 5, 20 m, while for all curves f = 300 MHz. If we consider that the calorific value of 1 m^3 of petroleum is 30 GJ, and the overall efficiency of the entire heating apparatus is 15%, then the energy break-even point is approximately 0.2 m^3/GJ (dashed line). As is evident from Fig. 6, heating efficiency has a maximum at low radiated powers (these maxima correspond to a small absolute increase in output). With increase in power the efficiency of heating decreases due to growth in thermal losses, but still exceeds the energy break-even point over the entire power range studied.

Thus, a numerical study of the process of electromagnetic heating of a petroleum stratum has been carried out with a two-dimensional model and consideration of convective heat transport and the temperature dependence of petroleum viscosity. It has been shown that the efficiency of heating depends significantly on proper choice of radiator frequency, power, and dimensions. The physical parameters used for the modeling were those of high viscosity petroleum characteristic of the Russian Tyumen' field. For those parameters an optimum radiator size of 0.4 m, optimum frequency of 300 MHz, and optimum power of 30 kW were obtained. For those values the calculated well output increased by 2.2 times (from 10 to 22 m^3/day), the maximum oil temperature did not exceed 250°C, heating efficiency was 4.5 m^3/GJ, and energy cost was 62 kWh for 1 m^3 of additional petroleum output. These results are quite usable from a practical standpoint, and the electromagnetic heating method is technically achievable and competitive, for example, with the intraplate combustion method.

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FORCED-CONVECTION HEAT TRANSFER FROM A HEATED SURFACE IN A CAVITY FORMED BY TWO HIGH FINS

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S. P. Tret'yakov, and N. I. Yarygina

UDC 536.24

Interest in the investigation of detached flows is due to the extensive engineering applications of such streams. It is well known [1] that the presence on a surface over which flow occurs of macroscopic roughness in the form of steps, fins, and grooves, resulting in detaching of the stream, can cause either intensification or a decrease in intensity of convective heat transfer. Intensification of heat transfer is caused by the additional turbulizing of flow in vortex zones, as well as the small thickness of the boundary layer in the zone of its reattachment to the wall and in the region of its further development downstream. A decrease in heat transfer is due to the small transfer coefficient in closed circulation zones ahead of and behind the obstacles. The influence of this factor increases with increasing height of the obstacles, when its relative value is $h^+ = hv^*/\nu \geq 10^2\text{-}10^3$ (h is the height of an obstacle, $v^* = \sqrt{\tau_w/\rho}$ is the frictional velocity, and ν is the kinematic viscosity).

The combined manifestation of these factors considerably complicates the process of heat and mass transfer, and a theoretical solution of the problem becomes very problematic. Experiment acquires primary importance in the analysis of such flows.

Despite the large number of papers that have been devoted to the experimental study of heat transfer in detached flows, the mechanism of heat transfer in a cell between two high fins has hardly been studied. Heat transfer behind a single high fin was mainly investigated in [2, 3]. A large number of papers have been devoted to the experimental study of hydrodynamics and heat transfer when there are roughness elements on a surface in the form of a system of

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