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Modeling of Microwave Heating and Oil Filtration in Stratum

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1. Introduction

Extraction of high-viscosity oil and bitumen is an important practical problem, because the reserves of such deposits are significant, and their role in common stocks of organic raw materials is constantly increasing. However, on account of the high viscosity of oil, and but also because of frequent blockage bottomhole zone due to sediments of colloidal surface-active components of oil extraction is becomes possible only after preliminary heat treatment of the stratum. Traditional methods of thermal treatment - hot steam or hot liquid - are in this case ineffective. Moreover, their widespread use may lead to severe environmental consequences in the form of violations of the hydrogeological environment.

One of the promising methods of thermal treatment is an electromagnetic heating of the productive layers. Due to deep penetration and the volumetric heat release, and absence of coolant, electromagnetic radiation can provide (compared to traditional methods) high speed and uniform heating, the possibility of optimal control and automation of technological processes, virtually eliminate the harmful effects on the environment. The results of laboratory and field trials in Russia (Sayakhov et al., 1970, Makogon et al., 1989, Sayakhov et al., 2002) and practical experience of using this technology on an industrial scale in the U.S. and Canada (Da Mata et al., 1997, Vermeulen & McGee, 2000, Sahni et al., 2000, Chhetri & Islam, 2008) show perspective utility of this trend. However, the effective realization of these opportunities is hindered by the lack of reliable data on the study of heat and mass transfer processes in multiphase media, typical for the oil and gas technologies, when subjected to these media microwave electromagnetic radiation. The main objective is to determine optimal modes of stimulation, namely: the frequency and power of a source of microwave radiation, the parameters of the antenna, the possibility of using nonlinear properties of the medium to enhance impact on the models as close as possible to real conditions.

In Russia, work on the effects of high frequency electromagnetic radiation on the oil reservoir was started in the late 60-ies by a team from Bashkir State University under the leadership of F.L. Sayakhov (Sayakhov et al., 1970, Sayakhov et al., 1975). Their industrial-scale plant was successful tested at Sushuglinsk' and Mordovo-Karmalsk' oilfields. At this industrial-scale plant, the electromagnetic energy from the high-frequency generator for the feeder (two coaxial tubes) is inserted into the well. The outer sheath of coaxial cable joins the casing and the central thread cable - to the tubing at a depth of about 5 meters, so that the

upper part of the column and tubing formed the short-circuited line, equal to 1/4 wavelength. Inside the tubing is submerged rod pump. Casing and tubing are used as a coaxial transmission line for supplying a high frequency electromagnetic energy to the radiator. The radiator consists of the lower casing and the bottom of the tubing, which stands below the casing with 1/4 wavelength (quarter-wave linear radiator). 2.5-inch duralumin tubes were used as tubing. A diameter of casing is 9 inches. Insulating washers (plastic ring 15 mm thick) placed every 8-10 m along the tubing, were used for insulation of tubing from the casing. Generator with an operating frequency of 13.56 MHz and output power (under optimal conditions) 63 kW was used as a source of high frequency electromagnetic radiation. The average yield before the start of heating was 0.1 m3/day; water cut was 30%. As a result of heating at the output power of 20-30 kW steady-state temperature set at 110 C after 7 days; yield increased to 0.25 m3/day, i.e. 2,5 times; water cut was reduced to 7-8%, i.e. more than 3 times. A well operated with a high yield flow rate for 17 days after the end of the electromagnetic effects.

In the U.S.A., research of electromagnetic effects on the oil wells was started in the late 70's. These studies culminated in a series of successful tests on the oil fields of the United States and Canada, and current technology of high-frequency electromagnetic radiation is reduced to a cost-effective and competitive level that allowed to move to its practical use in industrial scale. The effect of electromagnetic heating of the near-well zone can be illustrated by the tests carried out on the field in Alberta. To assess the effectiveness of the heating for this field computer simulations were carried out. The modeling predicted approximately twofold increase of well production by electromagnetic effects. The well was drilled in January 1986, and in March 1986 started production of oil. Up to the impact well gave about 6 barrels of oil per day. A month after the start of operation was launched electromagnetic heating. A few days later oil production increased and set at about 20 barrels per day, i.e. even higher than had been predicted by numerical simulation.

Successful tests were conducted in several other fields of the United States and Canada (in Oklahoma, Utah, Texas, California). Currently in the U.S.A. (New Jersey) the company Global Resource Corp. has been successfully working in this area. This company is a developer of a patented microwave technology and machinery that extracts oil and petroleum products from shale deposits, tar sands, capped oil wells, coals and processed materials such as tires and plastics as well as dredged soil from harbors and river bottoms. This process produces significantly greater yields and lower costs than are available using existing technologies.

Over the past 10-15 years several reviews of methods of electromagnetic heating for enhanced oil recovery (Da Mata et al., 1997, Vermeulen & McGee, 2000, Sahni et al., 2000, Chhetri & Islam, 2008) have been published.

Theoretical studies of heat and mass transfer in the oil stratum under the influence of high frequency electromagnetic radiation were carried out by teams of specialists under the leadership of R.I. Nigmatulin and F.P. Sayakhov (Zyunk Ngok Khai et al., 1987, Kislitsyn & Nigmatulin, 1990, Sayakhov et al., 1998, Sayakhov et al., 2002, Kovaleva et al., 2004).

The process of heating and filtration of bitumen in porous medium volume heat source, arising due to absorption of energy of electromagnetic waves was studied (Zyunk Ngok Khai et al., 1987). One-dimensional problem was solved taking into account the phase transition. They found a stationary solution for spherically symmetric source of electromagnetic waves and self-similar solution for a cylindrically symmetric source. Numerical simulation of the space heating and filtration of oil in the presence of a moving

front of melting was performed in the one-dimensional model. Quantitative estimates of the size of the heat zone were obtained. It was also pointed out to the danger that the source of too much power will cause overheating near wellbore zone. The negative consequences of such overheating are the decomposition of oil near the well, the deformation of the skeleton of porous rock, the destruction of wells, etc.

The theoretical study of heat and mass transfer in the oil stratum when it is heated by high-frequency electromagnetic radiation was performed on one- and two-dimensional models in research (Sayakhov et al., 1998, Sayakhov et al., 2002, Kovaleva et al., 2004, Kislitsyn, 1993, Kislitsyn, 1996). In these studies, considerable attention was paid to the propagation of electromagnetic waves in the oil reservoir and the distribution of the density of volumetric volume heat sources. The valuation of efficiency and cost effectiveness of the method in terms of energy balance has been made.

The filtration processes in porous media filled with a solid gas hydrate or liquid, with depression and thermal effects (including the electromagnetic heating), which leads to phase transitions (gas hydrate decomposition, boiling liquid) were studied in research (Shagapov & Syrtlanov, 1994). Optimal regimes of the heating stratum by using high-frequency electromagnetic radiation were determined to gas hydration control in the near wellbore zone.

Summarizing this brief review, it should be noted that there are a number of studies which examined the processes of heating and filtration of oil in stratums when exposed to high-frequency electromagnetic field. In these studies important results that may be used to estimate the depth and duration of heating and to select the optimal modes of exposure were obtained. Overall, however, the problem can not be well studied. In all the works cited above the equation for the electromagnetic field with the type of radiating antenna, temperature and frequency dependences of dielectric loss tangent of the medium wasn't used. Neglect of these circumstances can cause significant inaccuracies, and even erroneous results.

In this paper we propose a mathematical model closer to the actual conditions that includes two-dimensional system of interrelated equations of heat transfer and piezoconductivity, supplemented by the equation for the electromagnetic field with the type of radiating antenna, temperature and frequency dependence of dielectric loss tangent of the medium.

2. 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 2 is contained between planes perpendicular to the z-axis (1 - cap rock, 3 - underlying bedrock). 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 4 with an antenna is placed in the well. In this model, the antenna consists of a coaxial cable with a ring-shaped slot 7 cut on the outer conductor 6 from the short-circuited tip (5 - the central conductor of coaxial cable). The isolines of magnetic strength 8 in the coaxial cable, the petroleum stratum and the adjacent rock are shown in Fig.1.

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 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. 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 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 power is the basic task of our numerical modeling.
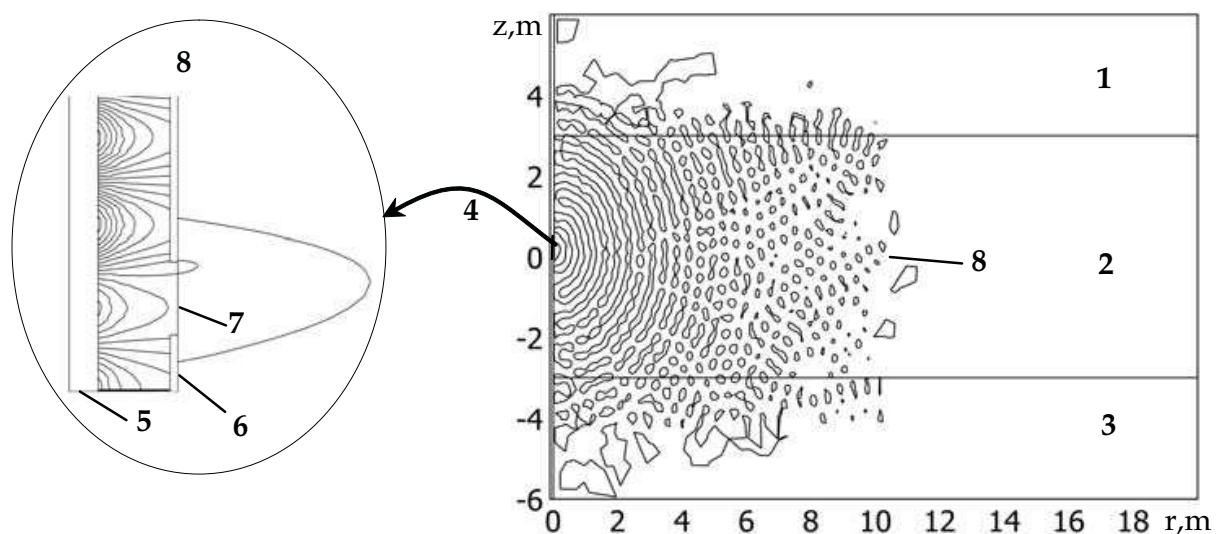

Fig. 1. A diagram of the model: 1 - cap rock; 2 - petroleum stratum; 3 - underlying bedrock; 4 - an electromagnetic radiation source with an antenna; 5 and 6 - a central conductor and an outer conductor of coaxial cable, respectively; 7 - a ring-shaped slot; 8 - isolines of magnetic strength

The model takes advantage of the problem's rotational symmetry, which allows modeling in 2D using cylindrical coordinates as indicated in Fig.1. When modeling in 2D, we can select a fine mesh and achieve excellent accuracy. The model uses a frequency-domain problem formulation with the complex-valued azimuthal component of the magnetic field as the unknown.

The radial and axial extent of the computational domain is in reality larger than indicated in Fig.1. This problem does not model the interior of the metallic conductors, and it models metallic parts using boundary conditions, setting the tangential component of the electric field to zero.

An electromagnetic wave propagating in a coaxial cable is characterized by transverse electromagnetic fields (TEM). Assuming time-harmonic fields with complex amplitudes containing the phase information, the appropriate equations are

$$\vec{E} = \vec{e_r}\frac{C}{r}e^{j(\omega t - k_0 z)} , \tag{1}$$

$$\vec{H} = \vec{e_\varphi}\frac{C}{rZ}e^{j(\omega t - k_0 z)} , \tag{2}$$

$$\vec{P}_{av} = \int_{r_{in}}^{r_{out}} \mathrm{Re}\left(\frac{1}{2}\vec{E} \times \vec{H}^*\right)2\pi r dr = \vec{e_z}\pi\frac{C^2}{Z}\ln\left(\frac{r_{out}}{r_{in}}\right) , \tag{3}$$

where z is the direction of propagation, and r, φ, and z are cylindrical coordinates centered on the axis of the coaxial cable. $\vec{P}_{av}$ is the time-averaged power flow in the cable, Z is the wave impedance in the dielectric of the cable, while r_{in} and r_{out} are the dielectric's inner and outer radii, respectively. Further, ω denotes the angular frequency. The propagation constant, k_0, relates to the wavelength in the medium, Λ, as

$$k_0 = \frac{2\pi}{\Lambda} \tag{4}$$

In the stratum, the electric field also has a finite axial component whereas the magnetic field is purely in the azimuthal direction. Thus, we can model the antenna using an axisymmetric transverse magnetic (TM) formulation. The wave equation then becomes scalar in H_φ:

$$\left(\nabla \times \left(\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right)^{-1}\nabla \times \vec{H}\right)\right)_\varphi - \mu_r k_0^2 H_\varphi = 0 , \tag{5}$$

where ε_r is the relative electric permittivity of the stratum; σ is the conductivity of the stratum; μ_r is the relative magnetic permittivity of the stratum.
The boundary conditions for the metallic surfaces are

$$\vec{n} \times \left(\vec{E_1} - \vec{E_2}\right) = 0 , \tag{6}$$

where $\vec{n}$ is the normal to the surface, the inferior indexes 1 and 2 relate to the stratum and the adjacent rock, respectively.
The feed point is modeled using a port boundary condition with a power level set to several tens of kilowatts. This is essentially a first-order low-reflecting boundary condition with an input field $H_{\varphi 0}$:

$$\left|\vec{n} \times \sqrt{\varepsilon}\vec{E}\right| - \sqrt{\mu}H_\varphi = -2\sqrt{\mu}H_{\varphi 0} , \tag{7}$$

where

$$H_{\varphi 0} = \frac{\sqrt{\dfrac{\vec{P}_{av}Z}{\pi r \ln\left(\dfrac{r_{out}}{r_{in}}\right)}}}{r} \tag{8}$$

for an input power of $\vec{P}_{av}$ deduced from the time-average power flow.

The antenna radiates into the stratum where a damped wave propagates. As we can discretize only a finite region, we must truncate the geometry some distance from the antenna using a similar absorbing boundary condition without excitation. Apply this boundary condition to all exterior boundaries. Finally, apply a symmetry boundary condition for boundaries at $r = 0$:

$$E_r = 0, \quad \frac{\partial E_z}{\partial r} = 0 \quad . \tag{9}$$

The volume heat source density is equal to the resistive heat generated by the electromagnetic field:

$$q(r, z, T, t) = \frac{1}{2} \mathrm{Re}\left[\left(\sigma - j\omega\varepsilon_r\right) \vec{E} \cdot \vec{E}^* \right], \tag{10}$$

where

$$\sigma = \varepsilon_0 \omega \varepsilon'' = \varepsilon_0 \omega \varepsilon_r tg\delta, \quad \varepsilon = \varepsilon_r - j\varepsilon'' \quad , \tag{11}$$

where ε'' is the imaginary part of the relative electric permittivity, $tg\delta$ is the dielectric loss tangent.

The heat equation describes the nonstationary heat transfer problem:

$$c\rho\frac{\partial T}{\partial t} + \nabla \cdot \left(-\lambda\nabla T\right) + mc_1\rho_1\vec{v}\cdot\nabla T = q(r, z, T, t) \tag{12}$$

where T is the temperature of the medium; c, ρ, λ are the specific heat capacity, density 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); c_1, ρ_1 are the heat capacity and density of the filtering liquid (petroleum); m is the porosity coefficient; $\vec{v}$ is the filtration velocity vector.

The process of oil filtration is described by equation of piezoconductivity:

$$\frac{\partial p}{\partial t} = \frac{1}{m\beta_p}\nabla \cdot \left(\frac{k}{\eta}\nabla p\right) + \frac{\beta_T}{\beta_p}\frac{\partial T}{\partial t} , \tag{13}$$

where p is the pressure, k is the permeability coefficient, η is the viscosity of the filtering liquid (petroleum), β_p is the compressibility coefficient, β_T is the thermal expansion coefficient of the filtering liquid.

Equations (12) and (13) are interrelated in that Eq. (12) considers convective heat exchange, which is dependent on pressure (Darcy's law):

$$\vec{v} = -\frac{k}{\eta}\nabla p , \tag{14}$$

while Eq. (13) 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

$$Ra = g\frac{\beta_T \rho_1^2 c_1 k}{\mu \lambda}\Delta TH \ll 1 \tag{15}$$

for any reasonable temperature head (H is the plate height).

The process of paraffin melting is accounted for in the following manner. It is assumed that the heat capacity within the stratum exhibits a singularity at the phase transition temperature T_s:

$$c(T) = c_0 + L\delta(T - T_s) \tag{16}$$

(L is the latent heat of phase transition and δ represents the delta function, which in numerical calculations is replaced by a "step" of finite width $2\Delta T_s$). Since the heatcapacity values for temperatures below and above T_s are different (c_0 and c_1, respectively), we can write the function $c(T)$ in the form

$$c(T) = \begin{cases} c_0 & \text{when } T < T_s - \Delta T_s, \\ \dfrac{c_0 + c_1}{2} + \dfrac{L}{2\Delta T_s} & \text{when } T_s - \Delta T_s \leq T \leq T_s + \Delta T_s, \\ c_1 & \text{when } T > T_s + \Delta T_s. \end{cases} \tag{17}$$

Initial and boundary conditions are as follows:

$$T\big|_{t=0} = T_0;$$
$$\frac{\partial T}{\partial r}\bigg|_{r=b} = 0, \quad \frac{\partial T}{\partial r}\bigg|_{r\to\infty} \to 0, \quad \frac{\partial T}{\partial z}\bigg|_{z\to\pm\infty} \to 0; \tag{18}$$
$$p\big|_{t=0} = p_0, \quad p\big|_{r=b} = p_b, \quad p\big|_{r\to\infty} \to p_0, \quad \frac{\partial p}{\partial z}\bigg|_{z=\pm H/2} = 0$$

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

Thus, the model is included in a system of two-dimensional interconnected equations of an electromagnetic wave propagating (5), heat transfer (12) and piezoconductivity (13) with appropriate boundary and initial conditions (18). The model takes into account phase transitions (process of paraffin melting) and temperature dependence of the dielectric loss tangent of oil.

In research (Kislitsyn & Fadeev, 1994) electric permittivity and dielectric loss tangent of certain types of high-viscosity oils (including Russian oil) in a wide range of frequencies and temperatures have been experimentally obtained. As a result, it was found that the dependence of complex permittivity ε on the frequency ω for oil is described by the model Havriliak-Negami (Havriliak & Negami, 1968):

$$\varepsilon = \varepsilon_r - j\varepsilon^{''} = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{\left[1 + (j\omega\tau_0)^{1-\beta}\right]^\gamma} + \frac{\sigma}{j\omega\varepsilon_0} , \quad 0 \le \beta < 1; \ 0 < \gamma \le 1 , \tag{19}$$

where ε_s, ε_∞ are static and high frequency limits of dielectric permittivity; τ_0 is the most probable relaxation time of molecules of the dielectric; β, γ are parameters characterizing respectively the width and asymmetry of the spectrum of relaxation times of the molecules of the dielectric. For $\gamma = 1$, this model goes into Cole-Cole model, and if more and $\beta = 0$, then the Debye model.

Sharing in the expression for ε the real and imaginary parts, we find

$$\varepsilon_r = \varepsilon_\infty + r^{-\gamma/2}(\varepsilon_s - \varepsilon_\infty) \cdot \cos(\gamma\vartheta) , \tag{20}$$

$$\varepsilon^{''} = r^{-\gamma/2}(\varepsilon_s - \varepsilon_\infty) \cdot \sin(\gamma\vartheta) + \sigma/\omega\varepsilon_0 , \tag{21}$$

where

$$r = \left[1 + (\omega\tau_0)^{1-\beta}\sin(\beta\pi/2)\right]^2 + \left[(\omega\tau_0)^{1-\beta}\cos(\beta\pi/2)\right]^2 , \tag{22}$$

$$\vartheta = arctg\left[\frac{(\omega\tau_0)^{1-\beta}\cos(\beta\pi/2)}{1 + (\omega\tau_0)^{1-\beta}\sin(\beta\pi/2)}\right] . \tag{23}$$

The temperature dependence of ε_r and ε_2 are determined by the temperature dependence of the parameters β, γ, τ_0 and σ model.

Developed in research (Kislitsyn & Fadeev, 1994) method of processing experimental data allowed us to determine with good accuracy the model parameters Havriliak-Negami for various high-viscosity oil Tyumen region. The values of parameters allow us to describe the behavior of oil in the electromagnetic field in a wide range of frequencies and temperatures, in particular the important characteristics as the dielectric loss tangent $tg\delta = \varepsilon^{''}/\varepsilon_r$, which affects the distribution of volume heat sources.

Figure 2 shows the dependence of dielectric loss tangent $tg\delta$ on temperature for oil of Russian field for a range of frequencies from 500 MHz to 2.4 GHz. The figure shows that with increasing oil temperature from the initial ($T_0 = 293$ K) to values of 330-360 K in the entire frequency range of the radiation the loss tangent increases approximately 1.5-fold, and then with further increase of temperature there is a decline of approximately 10 times when reaching decomposition temperature of the oil (about 530-550 K). Thus, the dependence of loss tangent with temperature for oil is nonlinear ("resonance") character, which significantly affects the process of heating oil electromagnetic radiation and should be considered when modeling this process.

Data on the viscosity of the Russian oil deposit depending on the temperature are obtained in (Kislitsyn & Fadeev, 1994). This dependence is well approximated by a generalized formula Andrade, which was used for modeling:

$$\eta(T) = \eta_\infty \exp\left\{E_\eta/R(T - T_s)\right\} , \tag{24}$$

where η_∞ is high-temperature limit of viscosity; E_η is activation energy of viscosity; T_s is temperature of complete solidification; R is universal gas constant.
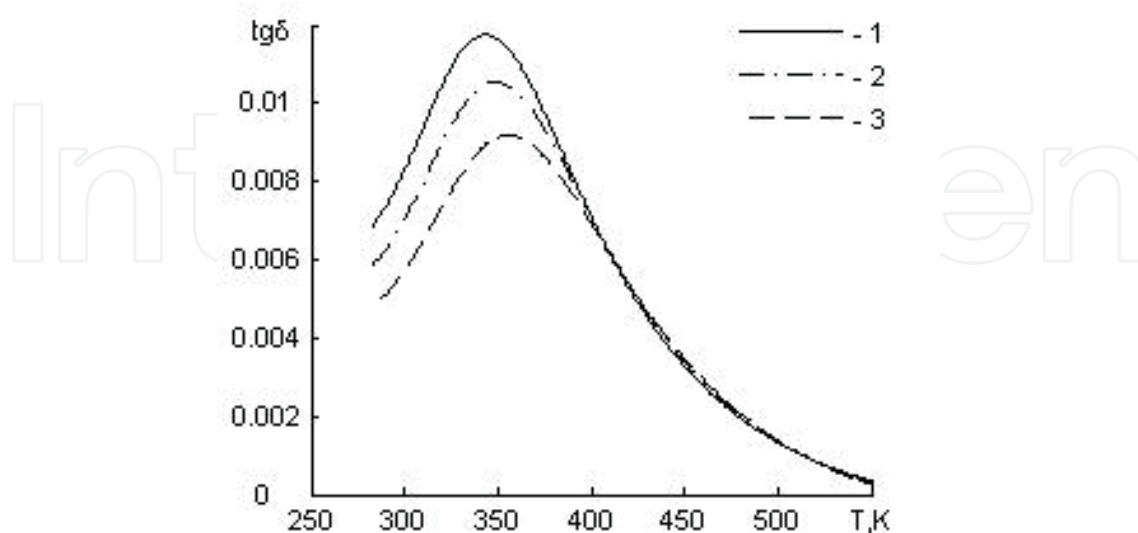

Fig. 2. The dependence of the dielectric loss tangent on temperature for oil Russian field for the frequencies: 1 - 500 MHz, 2 - 1 GHz, 3 - 2,4 GHz

Simulation of heating stratum was carried out by finite element commercial software package COMSOL Multiphysics. A numerical algorithm for the finite element method is based on the procedure of minimizing the functional corresponding to the continuous problem solved. The result of this procedure is the substitution of the system of partial differential equations system of algebraic equations with the coefficients approximating functions, which are actually the values of the unknown function at the vertices of the subdivision.

In the present research computational domain task was divided approximately into 40000 finite elements having the form of triangles. Finite element mesh was nonuniform. Concentration of elements was carried out in areas of expected strongest changes in temperature and electromagnetic field, i.e. near the radiation source and at the interfaces of the stratum-surrounding rock, where the size of finite elements was more than 10 times less than the wavelength of the radiation. As the basis functions piecewise-continuous quadratic Lagrange polynomials were used. The number of degrees of freedom of the problem was still approximately 170000. The numerical integration required to find the elements of the Jacobian, was carried out using the Gauss quadrature formula. To solve systems of linear algebraic equations was used Gaussian method, adapted to the use of very sparse matrices. The relative accuracy of calculations at each step of the iterative process was 0.01. Calculations were performed on a computer that has a processor with a clock speed of 3.33 GHz and 4 GB of RAM. Typical calculation time was approximately 60 hours.

In this research, a numerical study of electromagnetic heating oil stratum was carried out using physical parameters typical for heavy oil of the Russian Tyumen' field: oil density ρ_0 =940 kg/m³, density of the rock stratum ρ_1 =2200 kg/m³, density of the surrounding rocks ρ_2 =1580 kg/m³, volume heat capacity of oil c_0 =2310 kJ/(m³·K), average volumetric heat capacity of stratum c_1 =2310 kJ/(m³·K), volumetric heat capacity of the surrounding

rocks c_2 =2310 kJ/(m³·K), average thermal conductivity of the stratum λ_1 =1,0 W/(m·K), thermal conductivity of the surrounding rocks λ_2 =2,33 W/(m·K), average porosity of the reservoir 32%, melting heat L =160 kJ/kg. The values $\varepsilon_r(T)$, $\varepsilon''(T)$, $tg\delta(T)$, $\sigma(T)$ and $\eta(T)$, as a function of temperature, were determined by the above method.

2. Results and discussion

In this research the process of heating of stratum by electromagnetic radiation at frequencies f between 500 MHz and 2.4 GHz for 30 days was simulated. Heating time of stratum was chosen based on the fact that the typical heating time when using the traditional methods of heat treatment ranged from one to several months or even years. As a result of numerical study of the model based on equations (5), (12) and (13), supplemented by (10), spatial and temporal distribution of electromagnetic field, the volume density of electromagnetic energy, heat sources, temperature and viscosity were obtained. Some simulation results are shown in Fig. 3-6.
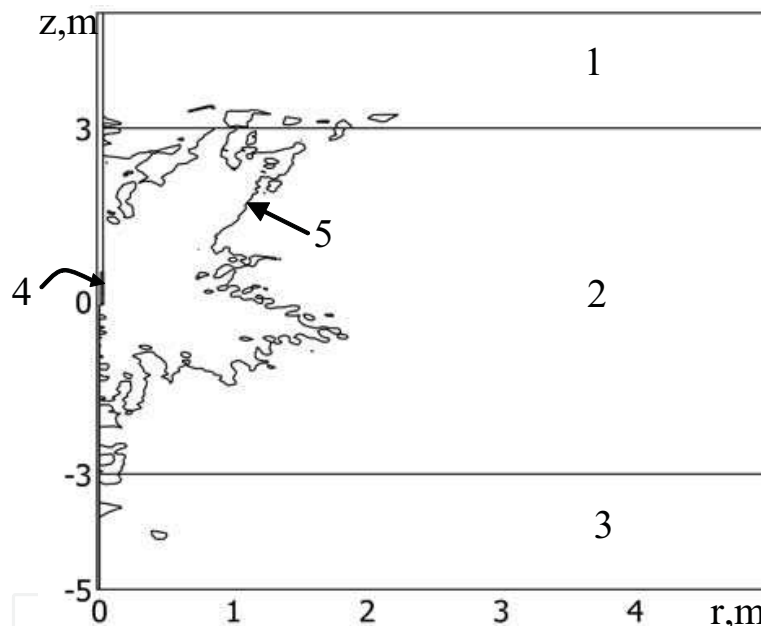
Fig. 3. The antenna diagram.
1 and 3 are top and bottom oil layer 2, 4 is a radiation source; 5 is isoline volume energy density of the electromagnetic field; radiation frequency f = 1 GHz and a power of W = 20 kW; time of heating the stratum is 10 days

The directivity and depth of penetration of radiation into the stratum can be judged by spatial distribution of volume energy density of the electromagnetic field, that is, in fact, this distribution characterizes the radiation pattern antenna. Figure 3 (1 and 3 are top and bottom oil layer 2, 4 is a radiation source) shows isoline volume energy density of the electromagnetic field 5 for the case of heating the stratum within 10 days of radiation source frequency f = 1 GHz and a power of W = 20 kW. Isoline 5 corresponds to the value of the energy density equal to $5 \cdot 10^{-6}$ J/m³. The figure shows that the radiation pattern of antenna radiation, being axisymmetric, has a complex spatial distribution of electromagnetic field, its

form changes with time of heating stratum due to temperature changes in the electrical properties of the medium. By integrating the energy density over the respective volumes values of the energy of the electromagnetic field in the stratum and surrounding rocks were obtained. Comparison of these values showed that approximately 94% of this energy falls on the stratum and only 6% on the surrounding rocks, indicating that sufficient performance directional antenna is used.

The calculations of temperature fields in the oil stratum allowed to determine the maximum allowable power source at a given frequency of radiation and the heating time of stratum. Power of the radiation source is necessary to limit the value at which the maximum temperature of oil, corresponding to the beginning of its thermal decomposition (approximately 530-550 K) is reached. Figure 4 shows the results of calculations of temperature in the stratum, depending on the radial distance from the source, obtained within the proposed model in the cases without (curve 1) and with (curve 2) temperature dependence of loss tangent (the radiation frequency f = 1 GHz , source power W = 20 kW, heating time 30 days). Thus, accounting of the temperature dependence of loss tangent has a significant impact on the calculations of temperature fields near the source of radiation. This is due to the fact that with increasing of oil temperature above 420 K, the values of loss tangent are considerably smaller (10 times at T = 530 K) than its value at the initial temperature of the stratum (Fig. 2), and therefore, in accordance with expression (2), decreases in proportion to the density of volume sources of heat, which slows down the heating stratum. The results of the calculations showed that when the heating time of 30 days of stratum and the radiation frequency f = 500 MHz, the maximum permissible power source is W = 30 kW, when the radiation frequency f = 1 GHz - W= 20 kW, when the radiation frequency f = 2,4 GHz - W= 5 kW.
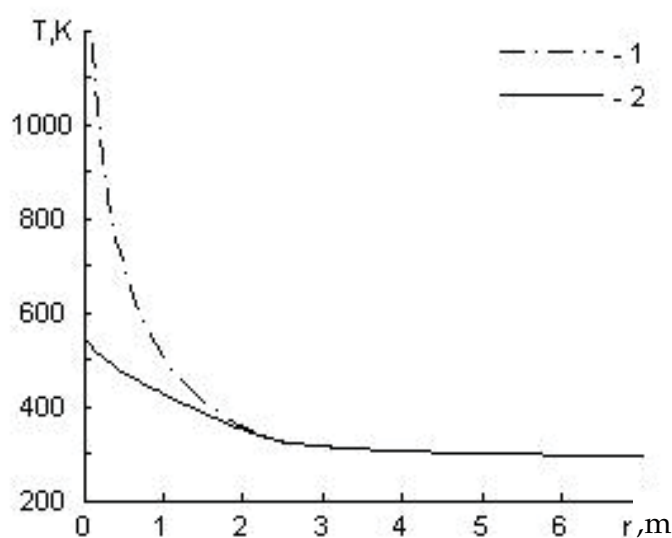

Fig. 4. The change of temperature in the stratum with the distance from the radiation source: without (curve 1) and with (curve 2) temperature dependence of loss tangent (the radiation frequency f = 1 GHz , source power W = 20 kW, heating time 30 days)
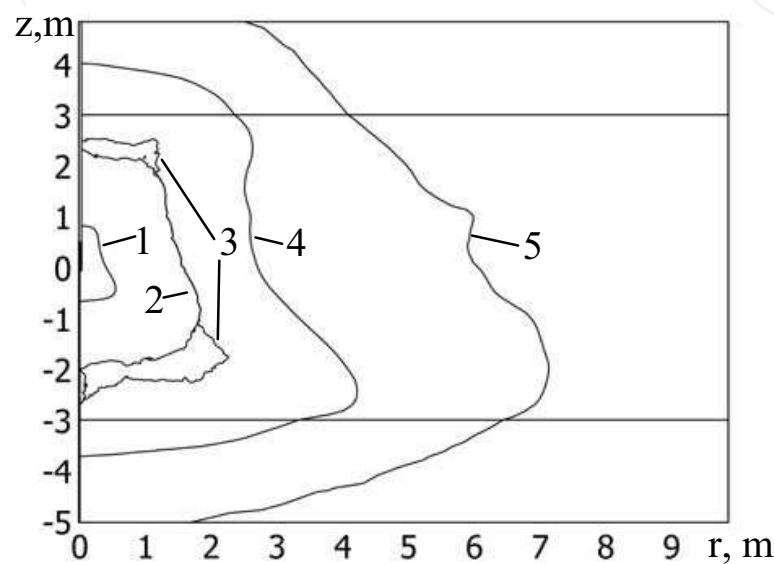
Figure 5 shows the isotherms of the temperature field after 10 days after the start of heating (source power W=20 kW, the radiation frequency f=1 GHz): curve 1 represents the isotherm

of 400 K, curves 2 and 3 are isotherms (323.05 K and 322.95 K), limiting the region of phase transition, 4 and 5 are isotherms 300 K and 294 K, respectively. In contrast to [7-9], where the phase transition is an infinitely thin front of melting, obtained in this study results indicate that under certain conditions, the extended region of phase transition (the area between the isotherms 2 and 3 in Figure 5) is formed. The distance at which the melting front moves along the axis r, and thus an important parameter of the process of heating - the volume of the melting zone - at a fixed heating time depends on the radiation frequency and power source.

Fig. 5. The isotherms of the temperature field after 10 days after the start of heating (source power W=20 kW, the radiation frequency f=1 GHz): curve 1 represents the isotherm of 400 K, curves 2 and 3 are isotherms (323.05 K and 322.95 K), limiting the region of phase transition, 4 and 5 are isotherms 300 K and 294 K, respectively
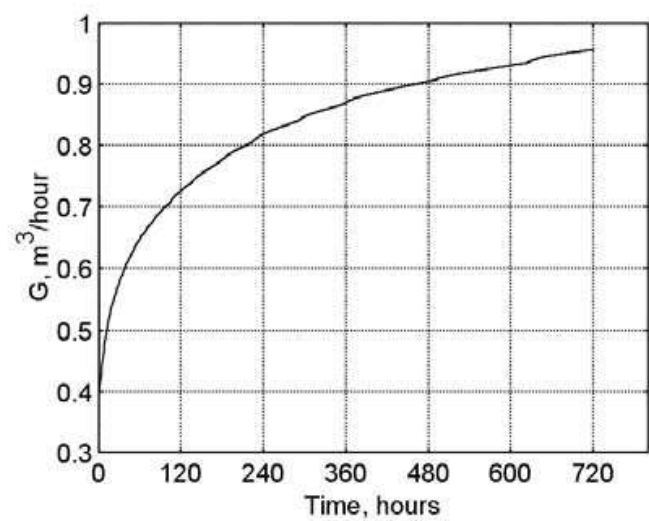
Fig. 6. Well yield as a function of heating time (frequency 1 GHz, power of source 30 kW)

Heating of oil reduces its viscosity, which, in turn, improves oil withdrawal. From a practical viewpoint the most important result of heating is the increase in well yield as compared to the yield of "cold" well. Figure 6 shows the dependence of increase in well yield as a function of heating time (optimal parameters for the Russian field: frequency 1 GHz, power of source 30 kW). The figure shows that this mode of heating leads to an increase well production by 2,3 times. At the same time energy costs account for about 60 kilowatt-hours per 1 m3 of additional oil production, which is quite acceptable from a practical point of view.

It has been shown that the efficiency of heating depends significantly on proper choice of radiator frequency and power. These results are quite usable from a practical standpoint, and the electromagnetic heating method is technically achievable and competitive, for example, with the in-situ combustion method. It is shown that high frequency microwave heating may be used for stimulating oil production high-viscous, low permeability stratum.

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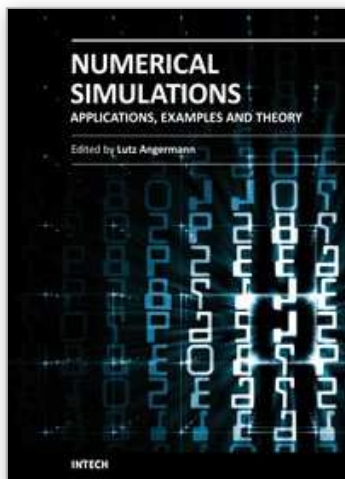
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