Computational studies of hydrotoparaffin plugs in wells

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Abstract. In Western Siberia and the Far North, complications caused by paraffin plugs in wells are not temporary. They are caused by ongoing factors, such as permafrost zones, a sharp temperature drop along the well, the high gas factor and water in the well products. The paper studies the possibility of using a high-frequency electromagnetic field to remove paraffin plugs inside the well. Mathematical modeling of the problem using a system of heat and mass transfer equations and boundary and initial conditions is described. The phase transition (melting of hydratoparaffin) is denoted by Stefan's condition which is one of the boundary conditions. The problem does not have an analytical solution, so the numerical implementation of the solution is carried out. Graphs of dependences of melting limits on generator power, and distribution of temperature fields in wells are constructed.

1. Introduction
The shortcomings in the use of the well fund in the oil and gas regions of Western Siberia and the Far North are due to the influence of natural-climatic, geological-physical and geological-fishing factors.

The deposition of solids in the walls of well pipes is associated with phase transitions occurring under certain thermodynamic conditions, i.e. with certain thermobaric conditions in the well. Conditions of phase transitions such as the deposition of solids are influenced by the presence of external physical fields (pressure, temperature, acoustic, vibration and electromagnetism) [1-3].

Therefore, the development of more effective methods of thermal impact on the bottomhole zone and oil reservoir, based on modern technological achievements and meeting environmental requirements is relevant and of great practical value.

The development of measures to prevent paraffin plugs in production wells is caused by modes of operation, pressure and temperature in the riser, the presence of water and the maximum possible index of gas temperature reduction [4-6].

Currently, there are a large number of methods to prevent paraffin deposits and eliminate existing traffic jams:

1. Mechanical cleaning or well overhaul (WO). Underground well repairs (UWR) make fluid circulation impossible, and the well requires long-term overhauls.

As the paraffin is deposited in the walls of the pipe, when the well has not yet been completely blocked, a "flying scraper" can be used. The device is lowered down, where it "opens" and, rising upwards, scrapes the deposits.

This method is widely used to eliminate existing traffic jams, but it is more cost-effective to prevent deposits. For this purpose, you can use the following technique:
2. Technological method. It involves the injection of chemical reagents (paraffin inhibitors), reducing the temperature of the phase transition. Solutions of methanol, diethylene glycol, etc. are usually used.

Technological methods of well treatment with different types of chemicals that prevent paraffin deposits should be developed for each region. They are influenced by field development systems, methods of well operation, abilities to deliver reagents directly to the tubing or through the annulus and possibilities of passing part of the product from the discharge line to the annulus and other features [7, 8].

3. Thermal method involves an artificial increase in temperature in various ways (steam injection, electromagnetic, induction heating, etc.).

One of the promising methods is application of effects arising from the action of physical fields - temperature field, pressure gradient field, elastic and electromagnetic and other wave fields [9, 10].

2. Physical fundamentals of the electromagnetic effect on paraffin deposits

The paper studies one of the cases of the thermal method - high-frequency electromagnetic heating of the well. Therefore, it is necessary to consider the physical basis of interactions of the electromagnetic field with the hydrate-paraffin plug.

The gas hydrate and substance of paraffin plugs have complex compositions and physicochemical properties. Under certain thermodynamic conditions, in paraffin a phase transition can occur and it melts.

The electromagnetic field can be described as a monochromatic field:

\[ \vec{E} = E_0 e^{i\omega t}, \vec{H} = H_0 e^{i\omega t} \]  

(1)

The substance of paraffin deposits in the electrophysical relation is a polarizing, weakly conductive, nonmagnetic dielectric with losses. This dielectric is characterized by the following electrophysical properties

\[ \varepsilon'(\alpha T, p) = \varepsilon \{ \varepsilon' \{ \alpha T, p \} - j \varepsilon'' \{ \alpha T, p \} \} \]

\[ \varepsilon'(\alpha T, p) \gg \sigma, \mu \gg \varepsilon, \varepsilon'' \approx \frac{\sigma}{\varepsilon} \]

(2)

where \( \omega = 2\pi f \) - circular frequency, \( f \) - frequency; \( \varepsilon' \) - complex dielectric constant of the medium, which depends on frequency \( \omega \), temperature \( T \) and pressure \( p \); \( \varepsilon', \varepsilon'' \) - real and imaginary parts of the relative complex dielectric constant; \( \sigma \) - specific electrical conductivity; \( \varepsilon'(r, \varphi, z) \) and \( \varepsilon''(r, \varphi, z) \) - vectors of complex amplitudes of electric and magnetic components of the high-frequency electromagnetic field, depending on the spatial cylindrical coordinates. The diagram below shows that in this case it is more convenient to use cylindrical coordinates for calculations.

For the medium with electrophysical characteristics (2) and a monochromatic high-frequency electromagnetic field (1), assuming the absence of charges and currents, Maxwell's equations can be written as:

\[ \text{Div} \vec{D}_0 = 0; \quad \text{Div} \vec{B}_0 = 0; \]

\[ \text{rot} \vec{H}_0 = j \omega \varepsilon_0 \vec{E}_0; \]

\[ \text{rot} \vec{E}_0 = -j \omega \mu_0 \vec{H}_0 \]

(3)

\( \vec{D}_0, \vec{B}_0, j \) are the amplitudes of the complex induction of the electric and magnetic fields and the imaginary unit.
Dependences can be found from the system of equations (3) \( \vec{E}_n(r, \varphi, z) \). The system of equations (3) can be reduced to the Helmholtz wave equation:

\[
\Delta \vec{E}_n + \Gamma^2 \vec{E}_n = 0; \quad \vec{H}_n = \frac{j}{\omega \mu_0} \text{rot} \vec{E}_n
\]

(4)

where the complex propagation constant \( \Gamma \) is determined as

\[
\Gamma^2 = -\omega^2 \mu_0 \varepsilon_0
\]

(5)

The energy interaction of the high-frequency electromagnetic field with the working dielectric medium characterized by the electrophysical properties (2) is determined by the appearance of distributed heat sources \( q_i \) whose densities are equal to

\[
q_i = \frac{\omega \varepsilon_0 E^*}{2} - \imath g \delta(E_0 \vec{E}_0^*)
\]

(6)

* denotes the complex-conjugate value.

In relation to the problem of destruction of paraffin plugs, the technological effect is achieved due to the following physical mechanisms:

- appearance of distributed heat sources as a result of their interaction with HF EMF (high-frequency electromagnetic field);
- uneven heating of the components of the inhomogeneous material and occurrence of thermoelastic stresses, which destroys sediments;
- an increase in temperature to the temperature of decomposition of hydratoparaffin stoppers in a large volume.

3. **Calculation studies of paraffin melting in a well**

Consider the case of destruction of a paraffin plug inside the compressor tube using electromagnetic wave energy. The destruction is possible by introducing electromagnetic energy directly into the tubing or into the intertube space.

Consider the case when electromagnetic energy is introduced into the intertube space (foam). The system consisting of a tubing and a casing is a coaxial line of transmission of electromagnetic waves from a ground generator. With the appropriate method of excitation, the mode of traveling waves is set. Due to the final electrical conductivity of the pipe material and dielectric losses of EM energy in the medium between the pipes, part of the EM wave energy is converted into thermal energy, and the temperature in the well increases. Due to an increase in temperature in the well, the paraffin plug is heated and melted.

High-frequency electromagnetic waves, propagating along the coaxial transmission line, lose their power due to losses on the metal walls and in the dielectric filling the tube space. In the coaxial HF EM transmission line, the wave propagates in the form of a transverse TEM wave, for which only the radial component of the electric field strength \( \vec{E}_r \) and the azimuthal component of the magnetic field strength \( \vec{H}_\varphi \) in the cylindrical coordinate system \( r, \varphi, z \) are different from zero \( \vec{E}_r \) and \( \vec{H}_\varphi \) for the transverse TEM wave in the coaxial system are obtained from the solution of equations (4). The longitudinal component of the Poynting vector in the cylindrical coordinate system for a coaxial transmission line has the form:

\[
\Pi_r = \frac{1}{2} \text{Re}(\vec{E}_r \cdot \vec{H}_\varphi^*)
\]

(7)

\( \vec{E}_r, \vec{H}_\varphi \) - the complex radial component of the electric intensity and the complex-conjugate
The azimuthal component of the magnetic field, respectively.

The density of distribution of heat sources along the transmission line created by the loss of electromagnetic energy in the metal walls and casing and in the dielectric filling the space between them are determined as

\[ q_z = \frac{2\alpha_i R_i}{\pi(R_i^2 - R_1^2)} e^{-2(\alpha_i + \alpha_3) z} \]  
\[ q_4 = \frac{2\alpha_i R_i}{\pi(R_i^2 - R_2^2)} e^{-2(\alpha_i + \alpha_3) z} \]  
\[ q_5 = \frac{2\alpha_5 P_0}{\pi(R_5^2 - R_3^2)} e^{-2(\alpha_i + \alpha_3) z} \]

\( \alpha_i \) - the attenuation coefficient of EM waves in the tubing; \( \alpha_4 \) - in the intertube; \( \alpha_5 \) - in the casing; \( R_1, R_2 \) - inner and outer radii of the tubing; \( R_3, R_4 \) - inner and outer radii of the casing; \( P_0 \) - EM wave generator power.

The total attenuation factor for the tubing, intertube and casing is

\[ \alpha = \alpha_3 + \alpha_4 + \alpha_5 \]

The attenuation coefficients of EM waves are determined as

\[ \alpha_3 = \frac{R_3}{2Z R_i \ln \left( \frac{R_i}{R_1} \right)}; \quad \alpha_5 = \frac{R_5}{2Z R_i \ln \left( \frac{R_i}{R_2} \right)} \]

\( R_{33} \) and \( R_{55} \) - active parts of the surface resistance of the tubing and casing:

\[ R_{33} = \sqrt{\frac{\pi \mu \sigma}{\sigma_3}}; \quad R_{55} = \sqrt{\frac{\pi \mu \sigma}{\sigma_5}} \]

where \( \mu_3, \mu_5, \sigma_3, \sigma_5 \) - absolute magnetic permeability and specific electrical conductivity of the tubing and casing, respectively, \( \text{Gn} / \text{m}, \text{Ohm}^{-1} \cdot \text{m}^{-1} \).

The attenuation coefficient of electromagnetic waves in the intertube space (foam) is determined as

\[ \alpha_4 = \omega \frac{\varepsilon_4 \mu_0}{2} \frac{1}{1 + t g^2 \delta_4} \left( \frac{1}{r \lambda} \frac{\partial T_i}{\partial r} \right) \]

where \( \varepsilon_4, t g \delta_4 \) - relative dielectric constant and tangent of the angle of dielectric losses of the medium in the intertube space.

### 4. Statement of thermodynamic problem

To determine the time of heating and melting of the paraffin plug in the tubing, the mathematical model of heat propagation in the well was developed. It was assumed that the medium filling the intertube space and surrounding the wellbore is homogeneous and isotropic.

The mathematical model of the process of destruction of the plug in the tubing during the propagation in the intertube space of HF EM waves is reduced to the solution of the system of equations of thermal conductivity in a multilayer medium:

\[ c_i \rho_i \frac{\partial T_i}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \lambda_i \frac{\partial T_i}{\partial r} \right) + q_i, i = 1, \ldots, 6 \]
\[ c_i \] - specific heat capacity, J / (kg \cdot K); \( \rho_i \) - density, kg/m\(^3\); \( \lambda_i \) - thermal conductivity, W / (m \cdot K). 1 refers to the solid phase hydrate inside the tubing \( 0 < r < R(t) \); 2 refers to the liquid phase of paraffin \( R(t) < r < R_1 \), which appears as it heats up in the well and occurs first near the wall of the tubing, then the area of the liquid phase gradually increases and reaches the center of the tubing. 3 refers to tubing \( R_1 < r < R_2 \); 4 refers to the dielectric filling the space between the tubing and the casing \( R_2 < r < R_3 \); 5 refers to tubing \( R_3 < r < R_4 \); 6 refers to the rocks surrounding the well \( R_4 < r < \infty \).

It is assumed that at the initial moment, the temperature in all layers of the well in the radial direction is the same. At the initial time \( t = 0 \), paraffin is solid. With depth, the initial temperature is higher in accordance with the geothermal gradient (0.03 °C / m), i.e.

\[ T_i(z) = T_0 + 0.03(z-10) \]  

\( T_{o0} \) – initial temperature at a depth of 10 m. From this depth, the temperature does not depend on seasonal temperature fluctuations.

\[ T_i(r,0) = T_o(z) \]  

At the maximum distance from the well axis \( r_m \) the temperature remains initial:

\[ T_i(r_m, t) = T_o(z) \]  

At the boundary of the well layers, the equality of temperatures and heat fluxes is observed:

\[ T(R_{i-1}, t) = T(R_{i+1}, t), \quad -\lambda_i \frac{\partial T_i(R_{i-1}, t)}{\partial r} = -\lambda_{i+1} \frac{\partial T_{i+1}(R_{i+1}, t)}{\partial r} \]  

When the phase transition temperature \( T_f \) is reached, melting begins. It is assumed that melting occurs on a moving surface of infinitesimal thickness \( R(t) \), i.e. Stefan's problem is solved as

\[ T_1(R,t) = T_f(R,t) = \Phi \]  

\[ -\lambda_1 \frac{\partial T_1(R,t)}{\partial r} + \lambda_2 \frac{\partial T_2(R,t)}{\partial r} = \rho L \frac{dR}{dt}, \]  

where \( L \) - specific heat of paraffin decomposition, J/kg.

Boundary value problem (15) - (22) is a nonlinear Stefan’s problem that does not allow an analytical solution. This problem was solved by the finite difference method according to an implicit scheme. In this case, a scheme with a fixed time step was selected and fractional spatial steps were used in determining the position of the phase boundary.

The initial temperature at a depth of \( z = 10 \) m is equal to \( T_0 = -10.4 \) °C. The temperature of the phase transition of paraffin is equal to \( T_f = 45 \) °C. The inner and outer radii of the tubing and casing are equal to: \( R_1 = 0.036 \) m, \( R_2 = 0.040 \) m, \( R_3 = 0.075 \) m, \( R_4 = 0.080 \) m.

The dielectric properties of foam for calculations are as follows: \( \varepsilon_4 = 1.1; \quad \tan \delta_4 = 0.0015 \). They were used to calculate the attenuation coefficients of electromagnetic waves - \( \alpha_3 = 0.000224 \) m\(^{-1}\); \( \alpha_4 = 0.000223 \) m\(^{-1}\); \( \alpha_5 = 0.000123 \) m\(^{-1}\).

The thermophysical properties of foam are \( c_4 = 502 \) J / (kg*K); \( \rho_4 = 50 \) kg/m\(^3\); \( \lambda_4 = 0.0232 \) W / (m*K), for the tubing and the casing: \( c_3 = c_5 = 502 \) J / (kg*K); \( \rho_3 = \rho_5 = 7900 \) kg/m\(^3\); \( \lambda_3 = \lambda_5 = 46 \) W(m*K).

Figure 1 shows the dynamics of the boundary of the phase transition of paraffin along the depth of the well. Generator power is \( P_0 = 50 \) kW. The dashed line is the inner radius of the tubing \( R_1 = 0.076 \) m. The initial temperature at a depth of \( z = 10 \) m is equal to \( T_0 = -10.4 \) °C.
Figure 1. Dynamics of the paraffin phase transition boundary. T = 57.6 hours, 86.4 hours, 115.2 hours, 144 hours, 172.8 hours, respectively.

100 hours after the generator was turned on, the plug melted to a depth of z = 60 m.

Figure 2 shows the dynamics of the paraffin phase transition boundary along the depth of the well at P₀ = 60 kW

Figure 2. Dynamics of the paraffin phase transition boundary. T = 57.6 hours, 86.4 hours, 115.2 hours, 144 hours, 172.8 hours.

Figure 2 shows that an increase in the power of the electromagnetic wave generator by 10 kW causes complete melting of the paraffin plug at a depth of up to 200 m after 140 hours of continuous heating.

The temperature distribution in the well in the range z = 10–260 m is presented in Figure 3. It can be seen that the temperature inside the tubing is closest to the wellhead, and behind the casing the temperature distribution is influenced by the geothermal gradient of 3°C per 100 m, so the temperature increases with depth due to the internal heat of the Earth.
Figure 3. Distribution of temperature on the radial coordinate at various depths in 3 days after the generator has been turned on. The dashed lines are the inner and outer radii of the tubing and the casing, respectively (from left to right).

In the intertube space, there is a thermal insulator (foam) so the temperature drops sharply from the heated area inside the tubing to the natural temperature of the rocks.

5. Conclusion

The paper analyzed the problem of melting paraffin plugs in a well under the influence of high-frequency electromagnetic fields. A geothermal gradient of 3°C per 100 m was taken into account. The temperature distribution along the length of the well from the mouth to $z = 260$ m at different points after the generator was turned on was obtained.

The dynamics of motion of the paraffin phase transition boundary depending on generator power was studied. Increasing the generator power reduces the heating and melting time of the plug. The impacts of differences between the formation temperature and the phase transition temperature $T_f - T_0$ on the dynamics of motion of the phase transition boundary were investigated.

The peculiarity of plug melting in the well - the phase transition – gradually occurs along the entire length of the well, starting from the mouth to the lower end of the plug. This process has a beneficial effect on the elimination of sediments, because extra pressure created at the top of the stopper by the liquid paraffin pushes it down to the bottom. Under the natural heat of the Earth, the plug melts.

The impact of high-frequency electromagnetic fields on the well is not limited to the plug elimination. A number of factors have a beneficial effect on oil production. Among them, a decrease in oil viscosity in the perforation zone, due to an increase in temperature in the well, which can increase the volume of oil production.

The modern electronics industry can manufacture sources of RF and microwave EMF, whose power can reach hundreds kW. Therefore, this method can be applied in the oil industry.

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