Numbridal simulation of a thermodynamic process to decompose gas hydrate in a gas production well using, radio-frequency electromagnetic radiation

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Abstract. The formation of gas hydrate deposits on the inner surface of gas production equipment is a frequently occurring type of complication in gas production, leading to a significant decrease in the useful section of pipes and gas pipelines. The intensity of their formation can lead to a complete overlap of the lifting pipes and annular channels in the annulus in certain areas, which necessitates repair work to clean the wells of gas hydrates. Based on the analysis of methods for cleaning wells from gas hydrate deposits, it was revealed that in some cases one of the effective methods of preventing their formation and combating them is to use the energy of high-frequency and superhigh frequency electromagnetic fields. The article explores the processes of heating and decomposition of gas hydrate deposits in the wellbore. About 30% of the thermal energy released in the wellbore interacting with the electromagnetic field is consumed to heat the medium surrounding the well. The need for timely removal of the gas-water mixture formed in the annulus for the decomposition of gas hydrate along the entire length of the well is established.

1. Introduction
In terms of electrodynamics, gas hydrates can be regarded as dielectrics possessing low electrical conduction [1]. When electromagnetic waves of the high-frequency and microwave frequencies are propagated in them, a change in the values of the dielectric constant is observed depending on the frequency of electromagnetic oscillations, caused by the adoption of a certain direction in space of the electric moments of the polar components, which causes loss of electrical energy in the dielectric This process is irreversible and heat is released in the volume covered by electromagnetic waves. The spatial dimensions of the volume of the medium in which the energy of the electromagnetic field is irreversibly converted into thermal energy depends on the oscillation frequency of the dipole molecules and the structure of the distribution of electromagnetic wave strengths and the values of the imaginary permittivity of the gas hydrate. Volumetric heat sources are created in the wellbore metal and gas hydrate, leading to an increase in the temperature of the gas hydrate and its splitting into gas and water. The use of the radio-frequency (or superhigh frequency) electromagnetic field energy seems to be attractive to revive wells and pipeline portions non-operative due to gas hydrate and paraffin block formation [2].
2. Mathematical simulation of a thermodynamic process

The paper presents a mathematical simulation of a thermodynamic process to decompose gas hydrate blocks by creating, inside a gas well, an radio-frequency electromagnetic field. The following assumptions have been made: the radio-frequency electromagnetic field energy of the power $P_0$ from the generator located at the well head ($Z=0$) is fed into the annular space of the well, in which the gas hydrate block has been formed; the tubing is filled with gas hydrate to the same height $H$ as the annular space; after the gas hydrate decomposition a gas and water mixture is produced both in the tubing and the annular space which possesses a constant voluminous gas content $\alpha_1$ and the said mixture is not removed; the gas and water mixture is characterized by some averaged values of physical parameters; no reflection of electromagnetic waves takes place from the “gas hydrate - gas and water mixture” interface; the transverse electromagnetic wave is propagated in the well annular space. Under the above assumptions the temperature in the well is described by the system of equations as below:

$$c_i \rho_i \frac{\partial T_i}{\partial z} = \frac{1}{r} \frac{\partial}{\partial r} \left( \lambda_i \frac{\partial T_i}{\partial r} \right) + \frac{\partial}{\partial z} \left( \lambda_i \frac{\partial T_i}{\partial z} \right) + q_i, \quad i = 1, ..., 7 \tag{1}$$

the together with boundary conditions

$$T_i = T_0 + T_z, \quad t = 0, \quad i = 1, ..., 7, \tag{2}$$

$$\frac{\partial T_i}{\partial r} = 0, \quad r = 0, \tag{3}$$

$$T_z = T_0 + r z, \quad r \to \infty, \tag{4}$$

$$-\lambda_i \frac{\partial T_i}{\partial r} = -\lambda_{i+1} \frac{\partial T_{i+1}}{\partial r}, \quad T_i = T_{i+1}, \quad r = R_j (i = 2, ..., 5; \quad j = 1, ..., 4), \tag{5}$$

$$-\lambda_2 \frac{\partial T_2}{\partial r} + \lambda_1 \frac{\partial T_1}{\partial r} = \rho_1 L \frac{d R_5}{d t}, \quad T_1 = T_2 = T_{R_5}, \quad r = R_5 (t), \tag{6}$$

$$-\lambda_4 \frac{\partial T_4}{\partial r} + \lambda_5 \frac{\partial T_5}{\partial r} = \rho_5 L \frac{d R_6}{d t}, \quad T_5 = T_5 = T_{R_6}, \quad r = R_6 (t), \tag{7}$$

$$\frac{\partial T_i}{\partial z} = 0, \quad z = 0, \quad z = H, \quad (i = 1, ..., 7). \tag{8}$$

In the above equations and the ones below the "1" index refers to the solid hydrate which fills the tubing, the "2" index refers to the gas and water mixture formed in the tubing, "3" – to the tubing, "4" , "5" – to the gas and water mixture and the solid hydrate, respectively, located in the annular space; "6" – to the casing string; "7" – to the surrounding rock (figure 1).

![Figure 1. Model Geometry. Tube concentric circumference radii $R_j = 0.065; 0.073; 0.128; 0.137$ m (j=1,...,4). Field frequency $f = 13.56 \cdot 10^6$ Hz, power at the well head $W_0 = 60kW$, lower edge of gas hydrate block $H = 700m$.](image-url)
Is depth interval in the well, at which the temperature increases by 1 °C (geothermal gradient), $T_p, L$ are, respectively, temperature of splitting and heat of conversion of gas hydrate into gas and water. Before the start of splitting of gas hydrate into gas and water in the tubing and the annular space the boundary conditions (5) are written as

$$-\lambda_i \frac{\partial T_i}{\partial r} = -\lambda_{i+2} \frac{\partial T_{i+2}}{\partial r}, T_i = T_{i+2}, r = R_j (i = 1,3; j = 1,2)$$  \hspace{1cm} (9)

The expressions for heat source distribution, incorporated in the equation system (1), are presented as

$$q_1 = q_2 = q_7, q_3 = \frac{K_{23} W_0 e^{-2K_2 r}}{\pi R_2} \delta (r - R_2), q_6 = \frac{K_{26} W_0 e^{-2K_4 z}}{\pi R_3} \delta (R_3 - r)$$  \hspace{1cm} (10)

$$q_4 = \frac{K_{24} W_0 e^{-2K_2 r}}{\pi r^2 \ln \frac{R_6}{R_2}}, q_5 = \frac{K_{25} W_0 e^{-2K_4 z}}{\pi r^2 \ln \frac{R_3}{R_6}}$$

The attenuation constant of the electromagnetic wave energy in the annulus consists of the attenuation coefficients in pipes, gas hydrate and a gas-water mixture, the numerical values of which depend on the magnetic permeability and electrical conductivity of the barrel materials, pipe radii, dielectric properties of solid gas hydrate, gas-water medium formed in the process of splitting the gas hydrate, the frequency of electromagnetic waves, and is expressed by the dependencies:

$$K_\alpha = K_{23} + K_{24} + K_{25} + K_{26},$$

$$K_{23} + K_{26} = \frac{R_5}{2Z_{d(1)} \ln \frac{R_3}{R_2}} \left( \frac{1}{R_3} + \frac{1}{R_2} \right), R_5 = \frac{\pi f \mu_m}{\sigma_m},$$

$$K_{27} = \frac{\omega \varepsilon'_w}{c_0} \sqrt{\left( \frac{e'_w}{e'_w} \right) \left( 1 + t g^2 \delta_4 - 1 \right) \ln \frac{R_a/R_2}{\ln (R_p/R_2)}} = K_{24} \frac{\ln (R_a/R_2)}{\ln (R_p/R_2)}$$

$$K_{25} = \frac{\omega \varepsilon'_w}{c_0} \sqrt{\left( \frac{e'_w}{e'_w} \right) \left( 1 + t g^2 \delta_6 - 1 \right) \ln \frac{R_5/R_3}{\ln (R_6/R_2)}} = K_{25} \frac{\ln (R_5/R_3)}{\ln (R_6/R_2)}$$

where $\varepsilon', t g \delta$–relative real part of imaginary permittivity and loss tangent of dielectrics (solid gas hydrate, gas-water mixture, gas, water); $\mu_m, \sigma_m$–absolute magnetic permeability and electrical conductivity of the medium of the fountain pipe and production casing, respectively.

It follows from expressions (13) and (14) that the attenuation coefficients and energy of electromagnetic waves in gas and water continuously change depending on the redistribution of volumes attributable to the gas-water mixture and solid gas hydrate [3]. The wave resistance of the gas-water mixture and gas hydrate in the space between the fountain pipe and the production string also depends on the volumes of gas hydrate and the media formed during the splitting:

$$Z_e(t) = \frac{\mu_0}{\varepsilon_0 \varepsilon_5} \frac{\ln (R_a/R_2)}{\ln (R_p/R_2)} = \frac{\ln (R_3/R_2)}{\varepsilon_6} + \frac{\ln (R_5/R_3)}{\varepsilon_5},$$

The relative real part of the dielectric constant and the tangent of the loss angle of the components of the gas-water mixture ($\varepsilon'_4, t g \delta_4, \epsilon'_4 = \varepsilon'_4 t g \delta_4$) are determined, in particular, from dependencies [4]:

$$\frac{[e'_4 - \varepsilon'_4 \sqrt{(e'_4 - \varepsilon'_4)^2 + (e'_g - \varepsilon'_g)^2}]^{\frac{1}{3}}}{[e'_g - \varepsilon'_g \sqrt{(e'_4 - \varepsilon'_4)^2 + (e'_g - \varepsilon'_g)^2}]^{\frac{1}{3}}} = (1 - \alpha_4)^2$$

$$\text{arctg} \frac{\varepsilon'_4 e'_g - e'_4 e'_g}{\varepsilon'_4 e'_g + e'_4 e'_g} = 3 \text{arctg} \frac{(e'_4 - \varepsilon'_4)(\varepsilon'_4 - e'_w)(e'_4 - \varepsilon'_4)(e'_4 - e'_w)}{(e'_4 - e'_w)(\varepsilon'_4 - e'_w)(\varepsilon'_4 - e'_w)}$$

(16)
In the system of heat conductivity equations (1), the volumetric heat capacity of the gas-water mixture is expressed by the dependence

\[ c_i \rho_i = c_g \rho_g \alpha_g + c_w \rho_w (1 - \alpha_g), (i = 2, 4). \] (17)

In Expressions (16) and (17), the indices “w” and “g” express the differences between a liquid and a gas in the composition of a gas-water mixture, respectively.

The temperature of the splitting of the gas hydrate (in °C) and the pressure \( P_b \) (in atmospheres) at which the gas hydrate is formed or split, are interconnected [5]:

\[ T_b = 9.75 lg P_b - 0.7. \] (18)

As the depth of the well increases, the pressure in the wellbore rises, which leads to a nonlinear increase in the splitting temperature of the solid gas hydrate plug along its length. By approximating experimental data [5] obtained for one well, the following dependence can be recorded:

\[ P_b = P_{yp} e^{0.000136z}, \]

where \( P_{yp} \) is hydrate formation pressure at the well head.

Table 1 presents the values of the physical parameters of the media included in the system of equations (1) - (8) together with conditions (9) - (19), adopted in computer studies of the dynamics of decomposition of gas hydrate in the gas well of the Sredne-Vilyui field of the Republic of Yakutia-Sokha (according to [7-12]).

As follows from table 1, the thermal conductivity of the metal is much greater than that of gas hydrate, water and gas. Therefore, with a small wall thickness of the barrel pipes, the characteristic time for temperature equalization in them is insignificant, which determines the instantaneous transfer of heat to the media filling and surrounding the well. Therefore, heat sources distributed over the fountain pipe and production casing, interacting with the electromagnetic field, are described by the dependencies:

\[ q_3 = \frac{K_{23} W_0 e^{-2K_2z}}{\pi r^2 \ln \frac{R_2}{R_1}}, q_6 = \frac{K_{26} W_0 e^{-2K_5z}}{\pi r^2 \ln \frac{R_4}{R_3}}. \]

**Table 1. Physical characteristics of the media used in the simulation study.**

| Medium     | \( \rho \) | \( c \) | \( \chi \) | \( \alpha_7 \) | \( t_\delta \) | \( \mu_{nm} \cdot 10^{-7} \) | \( \sigma_m \cdot 10^{-7} \) |
|------------|------------|--------|--------|-------------|-------------|----------------|----------------|
| Hydrate*   | 689        | 2880   | 0.38   | -           | 4.17\bf{b}  | 0.1\bf{b}      | -              |
| Water*     | 1000       | 4117   | 0.585  | -           | 78.2        | 0.0046         | -              |
| Gas*       | 188        | 3407   | 0.066  | 0.48        | 7           | 0              | -              |
| Metal      | 790        | 502    | 46     | -           | -           | 34.16          | 0.34           |
| Rock       | 2080       | 1400   | 3.62   | -           | -           | -              | -              |

\* \( p, c, \chi, \alpha_g \) are assumed for pressure 20 MPa,
\bf{b} according to data from [1, 2].

**3. Results**

The results of computer studies of the above mathematical model describing the dynamics of decomposition of gas hydrate in the wellbore, interacting with a high-frequency electromagnetic field, and taking into account the thermal properties of the environments are expressed in figures 2-4.
4. Discussion

The temperature over the cross section of the well is unevenly distributed: in the initial times of electromagnetic exposure, the maximum temperature value is predicted on the outer surface of the fountain pipe (figure 2). With increasing duration, the fountain pipe heats up faster than the inner wall of the production casing. After the gas hydrate splitting temperature is reached, the rate of temperature increase on the outer surface of the fountain pipe is significantly reduced, and on the inner surface of the production string it accelerates, which indicates an increase in heat loss to the medium surrounding the well.

The spatio-temporal temperature change resulting from figure 2 is manifested in the dynamics of decomposition of gas hydrate in the wellbore. So, gas hydrate splitting in the annular space begins earlier than in the fountain pipe (figure 3). Such a feature in the dynamics of decomposition is associated with the direct interaction of gas hydrate with the electromagnetic field created in the annulus of the well. Gas hydrate in the annulus completely decomposes much faster than in the fountain pipe.
Figure 4. The dynamics of temperature over time in the depth of the well (1 – 0.6; 2 – 2.9; 3 – 5.8; 4 – 34; 5 – 67; 6 – 120; 7 – 216; 8 - $T_p - T_0$, 9 – initial temperature distribution along the well depth).

One of the reasons for this is great energy required to decompose the hydrate in the tubing. Moreover, $K_\alpha$ decreases according to the exponential law as seen from figure 3 (curve 1), i.e. $K_\alpha$ - is a physical parameter that nonlinearly depends on the time of decomposition of the gas hydrate in the space between the production string and the fountain pipe, and the dielectric losses in the gas-water mixture are much smaller than in the gas hydrate. ($K_{\alpha 4} = 0.00296 \text{ m}^{-1}, K_{\alpha 5} = 0.03 \text{ m}^{-1}$). According to the data presented in figure 2, it also follows that about 30% of the thermal energy released in the wellbore interacting with the electromagnetic field is consumed to heat the medium surrounding the well. To reduce such significant heat loss and ensure well stability in permafrost conditions, it is necessary to develop technological measures.

A high-frequency electromagnetic field leads to a significant change in the temperature distribution over the depth of the well, therefore, a change in the geothermal gradient in the conditions of a particular well (figure 4).

5. Conclusions
Mathematically simulated the process of heating and destruction of a gas hydrate plug in a gas well using the energy of the RF electromagnetic field.

Numerical studies of the process of splitting a gas hydrate interacting with a high-frequency electromagnetic field in a gas wellbore at physical parameters typical of the Sredne-Vilyui field of the Republic of Yakutia-Sokh have been carried out.

A no monotonic change in temperature in the well was revealed: the maximum temperature is reached on the outer wall of the fountain pipe, its growth rate is greater than on the production casing. Such a feature in the dynamics of decomposition is associated with the direct interaction of gas hydrate with the electromagnetic field created in the annulus of the well. Gas hydrate in the annulus completely decomposes much faster than in the fountain pipe.

In the nodes of the well pipes, where the gas hydrate directly interacts with the electromagnetic field, the decomposition of the gas hydrate begins earlier and is quite intense. The interconnection between the processes of decomposition of hydro hydrate and the interaction of the electromagnetic field with it has been established: the attenuation coefficient of electromagnetic waves in the annulus decreases linearly with time, the rate of decomposition of gas hydrate in it decreases and electromagnetic waves penetrate far enough deep into the well.

About 30% of the thermal energy released in the wellbore interacting with the electromagnetic field is consumed to heat the medium surrounding the well. To reduce such significant heat loss and ensure well stability in permafrost conditions, it is necessary to develop technological measures.

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