SCIENTIFIC JOURNAL
EARTH'S CRYOSPHERE

Earth`s Cryosphere, 2016, vol. XX, No. 1, pp. 60–63 **http://earthcryosphere.ru/**

GAS HYDRATE FORMATION

PREDICTION OF THERMAL INTERACTION BETWEEN OIL/GAS WELLS AND INTRA-PERMAFROST METASTABLE GAS HYDRATES

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A model for thermal interaction between the production well and permafrost strata containing relic metastable hydrates has been developed for evaluation of the intensity of permafrost thawing and gas emissions associated with the development of oil and gas fields in northern areas. A self-similar solution and analytical expression for the phase boundary estimation have been obtained. The formula for propagation of the radius of thermal influence of production wells has been developed, with the influence of hydrate saturation of rocks and cement sheath heat conductivity on the thawing radius deduced from the self-similar solution.

Metastable gas hydrates, gas emission, boundary of phase transition, radius of the thermal influence of production wells

INTRODUCTION

The intensive development of oil and gas fields in the permafrost-ridden northern regions is frequently associated with sudden releases of flammable gases caused by fluids escaping at the wellhead. Such incidents are most critical in the field operations on the Yamal Peninsula and adjacent Kara Sea offshore areas. More and more commonly, these gas liberations are associated with the hydrate-bearing interlayers at depths ranging from a few meters up to 200–250 m within the interval of the overlying perennially frozen deposits. Gas hydrates are held in them in a preserved metastable state and are termed "relic gas hydrates", with their gaseous part dominated primarily by methane in composition [*Yakushev, 2009*]. Given that in nature, self-preserved hydrates are stored in hard-frozen permafrost as long as they are enveloped by ice film, they are extremely sensitive to natural and technogenic impacts. Among them, thermal influence appears the most significant, inasmuch as it is capable of aggravating any other impacts. The thawing of ice-rich sediments hosting gas hydrates evokes the processes of decomposition, followed by the adequate gas liberation. As is known, high-hazard emergency situations caused by the "ice–water–hydrate–gas" phase transitions may occur during the life cycle of oil or natural gas well. The relationship between the phase state of rocks and the potential unfavorable implications for the drilling operations are discussed in [*Vasil'eva et al., 2011*].

In case of poorly cemented wellhead (which may be due to the presence of gas hydrates) and insufficient heat conservation insulation, the thermal pulse from oil or gas flow will expand into the surrounding sediments, with a thawing halo gradually forming around it and propagating through the permafrost thickness, which is, for instance, characteristic of the Yamal Peninsula section within the uppermost 200–300 m depth interval.

Similar to ice, gas in the hydrate form acts as a cementing agent between the mineral particles, therefore, the thawing of permafrost leads to loss of stability within ice-filled rocks, and thus causing changes in distribution of in-situ stresses and axial loads on the casing string. Along with these, the intensification of caving processes subsequent to the metastable gas hydrate decomposition and thawing of ice cement appears one of the most critical implications [*Vasil'eva et al., 2011*].

In order to evaluate the intensity of permafrost thawing and associated gas release into the atmosphere, it would be most appropriate to study in detail the model of thermal interaction between the producing well and permafrost strata holding relic metastable gas hydrates. The existing methods for thermal calculations allow to define thermal field of rocks on the assumption of constancy of oil or gas temperature in the well, or its constancy on the borehole wall (stationary problem) [*STO Gazprom...*, *2008*], or constancy of only fluid temperature in the well (dynamic problem) [*Korotaev et al., 1976; Istomin, 1981*]. Type I boundary conditions are accepted in the first case, whereas type III boundary conditions are applicable in the second and third cases.

Inasmuch as the well and the surrounding rock form a single heat exchange system, both the fluid temperature in the well and the rocks temperature are assumed to be variable in this paper, while the heat flow on the borehole wall is considered to be constant, i.e. boundary conditions are taken to be type II.

PROBLEM FORMULATION

The paper addresses the issue of soil thawing around a natural gas producing well consisting of a production string with inner radius r_0 and cement sheath with outer radius r_c. The surrounding rocks have initial saturation of pore space with ice (s_{i0}), hydrate (s_{h0}) and water (s_{w0}). While the well is operating, gas flows through it with a temperature $T_g = 303$ K (+30 °C), which provokes a time-dependent, progressively increasing thaw halo ($r_c \le r < R_*(t)$), conjugated to the frozen zone ($R_*(t) \le r < \infty$). Here, $R_*(t)$ is a moving phase boundary, m; t – time, s. Given that the considered interval of borehole is significantly greater than the thawing radius, the heat flow in a vertical direction will be neglected, and we have thus a linear problem with axial symmetry.

In the *thawed zone* of coexisting gas and water, the law of energy conservation proves applicable

$$\text{at } r_c \le r < R_*(t): \; \frac{\partial T_1}{\partial t} = a_1 \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_1}{\partial r}\right),$$

$$a_1 = \frac{\lambda_1}{(c\rho)_1}, \qquad (1)$$

where a_1 is temperature conductivity; $(c\rho)_1 = \rho_s c_s(1-m) + \rho_w c_w s^0 m + \rho_g c_g\left(1-s^0\right)m$ is the product of heat capacity by density of thawed zone; $\lambda_1 = \lambda_s(1-m) + \lambda_w s^0 m + \lambda_g\left(1-s^0\right)m$ is thermal conductivity of thawed zone, W/(m·K); m is porosity; ρ is density, kg/m^3; c specific heat, J/(kg·K); T_1 is temperature of thawed zone, K.

Here s^0 is undisturbed water saturation in the water-gas zone, which is a function of the initial values of hydrate-, ice- and water-saturation:

$$s^0 = s_{i0}\,\rho_i/\rho_w + s_{h0}\rho_{0w}/\rho_w + s_{w0},$$

where ρ_{0w} is effective density of water in hydrate (mass of water per unit volume of hydrate), kg/m^3. Indices *w, h, g, i, s* correspond to water, hydrate, gas, ice and porous matrix, respectively.

In the *frozen zone* of water, hydrate and ice coexistence the law of energy conservation is fulfilled

$$\text{at } r_c \le r < R_*(t): \; \frac{\partial T_2}{\partial t} = a_2 \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_2}{\partial r}\right), \; a_2 = \frac{\lambda_2}{(c\rho)_2}, \qquad (2)$$

where $(c\rho)_2 = \rho_s c_s(1-m) + \rho_i c_i s_i m + \rho_h c_h s_h m + \rho_w c_w\left(1-s_h-s_i\right)m$ is product of heat capacity by density of frozen zone; $\lambda_2 = \lambda_s(1-m) + \lambda_i s_i m + \lambda_h s_h m + \lambda_w\left(1-s_h-s_i\right)m$ is heat conductivity of frozen zone; T_2 is temperature of frozen zone.

Initial and boundary conditions are taken as

$$\text{at } t = 0,\; r > r_c: \; T = T_0,\; s_i = s_{i0},\; s_h = s_{h0}; \qquad (3)$$

$$\text{at } r = \infty,\; t > 0: \; T_2(r) = T_0; \qquad (4)$$

on the moving phase boundary

at $r = R_*(t)$:

$$\left(\lambda_2\frac{\partial T}{\partial r}\right)^+ - \left(\lambda_1\frac{\partial T}{\partial r}\right)^- = m\left(\rho_h q_h s_h^+ + \rho_i q_i s_i^+\right)\frac{dR_*}{dt}; \qquad (5)$$

$$T_1(r)^+ = T_2(r)^- = T_*. \qquad (6)$$

Here, T_* is temperature of thawing ground, K; T_0 is in-situ temperature of hard-frozen ground, K; q_h, q_i is latent heat of phase transition of hydrate and ice, respectively, J/kg.

The *boundary condition*, which is a matching condition for gas temperature fields in wellbore and rocks with gas moving through them, is taken as

$$\text{at } r = r_c,\; t > 0: \; k_D\left(T_2 - T_c\right) = -\lambda_1\frac{\partial T}{\partial r} = \frac{W}{2\pi h r_c}, \qquad (7)$$

where T_c is average temperature for the length of the considered borehole interval on the cement sheath surface; W is heat flux cycling through the outer surface of the cement column, W·m^2/s; the heat-exchange coefficient is written as

$$k_D = \left[\frac{1}{\alpha} + \frac{r_c}{\lambda_c}\ln\frac{r_c}{r_0}\right]^{-1}. \qquad (8)$$

The coefficient convective heat transfer α between gas and the inner surface of pipe depends on the gas flow properties such as velocity and is defined by the empirical equation [*STO Gazprom..., 2008*]:

$$\alpha = 5.42\cdot 10^{-3}\, V^{0.8}\big/\left(2r_0\right)^{0.2}, \qquad (9)$$

where V is flowing gas velocity, m/h.

SELF-SIMILAR SOLUTION

Given that the initial and boundary functions of temperature, hydrate saturation and ice content (T_0, W, s_{h0}, s_{i0}) are constant, the problem (1)–(9) admits a self-similar solution:

$$T = T(\xi),\; R_* = \delta t^{1/2},\; \xi = rt^{-1/2}.$$

The self-similar solution of the problem for thawed zone is written as

$$\text{at } \xi < \delta: T_1 = T_* + \frac{W}{4\pi h\lambda_1}\left[Ei\left(-\frac{\delta^2}{4a_1}\right) - Ei\left(-\frac{\xi^2}{4a_1}\right)\right], \qquad (10)$$

where $Ei\left(x\right) = -\int\limits_{-x}^{\infty}\frac{e^{-t}}{t}dt$ is the exponential integral.

The self-similar solution of the problem for frozen zone is written as

$$\text{at } \delta < \xi < \infty\text{: } T_2 = T_0 - \frac{T_0 - T_*}{Ei\left(-\delta^2/(4a_2)\right)} Ei\left(-\frac{\xi^2}{4a_2}\right). \quad (11)$$

Condition (5) at phase boundary, in the self-similar variables, takes the form

at $\xi = \delta$:

$$\left(\lambda_2 \frac{dT}{d\xi}\right)^+ - \left(\lambda_1 \frac{dT}{d\xi}\right)^- = m\left(\rho_h q_h s_h^+ + \rho_i q_i s_i^+\right)\frac{\delta}{2}. \quad (12)$$

Substituting solutions (10), (11) into boundary conditions at the moving boundary (12), we will find an integral equation for determining parameter δ:

$$4\lambda_2 \frac{T_* - T_0}{Ei\left(-\delta^2/(4a_2)\right)} \exp\left(-\frac{\delta^2}{4a_2}\right) + \left(\frac{W}{\pi}\exp\left(-\frac{\delta^2}{4a_1}\right)\right) =$$

$$= m\left(\rho_h q_h s_h^+ + \rho_i q_i s_i^+\right)\delta^2. \quad (13)$$

Defining radius of thermal influence of gas well

When planning a field development project it is critical to be able to predict the permafrost thaw dynamics both in the area around boreholes and projected zones of thermal affect. If the radius of thermal influence of the well is taken as current radius value $R_T(t)$, where the temperature deviation from the initial value is equal to a given small value ε, then the problem solution in the frozen zone (11) yields an integral equation for its determination

$$T_2 - T_0 = \varepsilon = \frac{T_* - T_0}{Ei\left(-\delta^2/(4a_2)\right)} Ei\left(-\frac{R_T^{\,2}}{4a_2 t}\right). \quad (14)$$

As follows from (14), the radius of a thaw halo around the wellbore is controlled by difference between the initial temperature and the phase transition temperature, by the phase transition front propagation velocity, and by temperature conductivity of the frozen zone. Given the initial temperature is equated with the transition temperature, the thermal influence of the borehole does not extend beyond the phase transition front, which corresponds to one-phase Stefan problem.

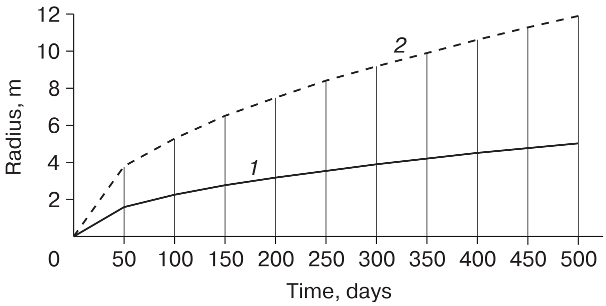

Fig. 1. Dependence of thawing radius (*1*) and thermal influence of wells (*2*) on time.

CALCULATION RESULTS

Figs. 1 and 2 depict the results of calculations performed using the MathCAD software, given the following values of the parameters characterizing the permafrost strata in the northern West Siberia and properties of the materials used in the construction of wells: $T_* = 271$ K, $T_0 = 268$ K, $r_0 = 0.084$ m, $r_c = 0.45$ m, $m = 0.45$, $s_{i0} = 0.76$, $s_{h0} = 0.15$, $\rho_s = 2000$ kg/m^3, $\rho_w = 1000$ kg/m^3, $\rho_h = 900$ kg/m^3, $\rho_i = 900$ kg/m^3, $\rho_{0g} = 116$ kg/m^3, $\rho_{0w} = 784$ kg/m^3, $c_s = 966$ J/(kg·K), $c_w = 4200$ J/(kg·K), $c_h = 2100$ J/(kg·K), $c_i = 2050$ J/(kg·K), $c_g = 2200$ J/(kg·K), $\lambda_s = 2.0$ W/(m·K), $\lambda_w = 0.58$ W/(m·K), $\lambda_g = 0.034$ W/(m·K), $\lambda_h = 0.5$ W/(m·K), $\lambda_i = 2.21$ W/(m·K), $\lambda_c = 1.4$ W/(m·K), $q_h = 43.7 \cdot 10^4$ J/kg, $q_i = 33 \cdot 10^4$ J/kg.

Fig. 1 shows the progression rate of thawing radius around a natural gas well at a flow temperature +30 °C, with the cement column thickness 0.27 m and thermal conductivity of the cement sheath 1.4 W/(m·K). Over one year, the radial distance of thaw reached 4.3 m, and the radius of thermal influ-

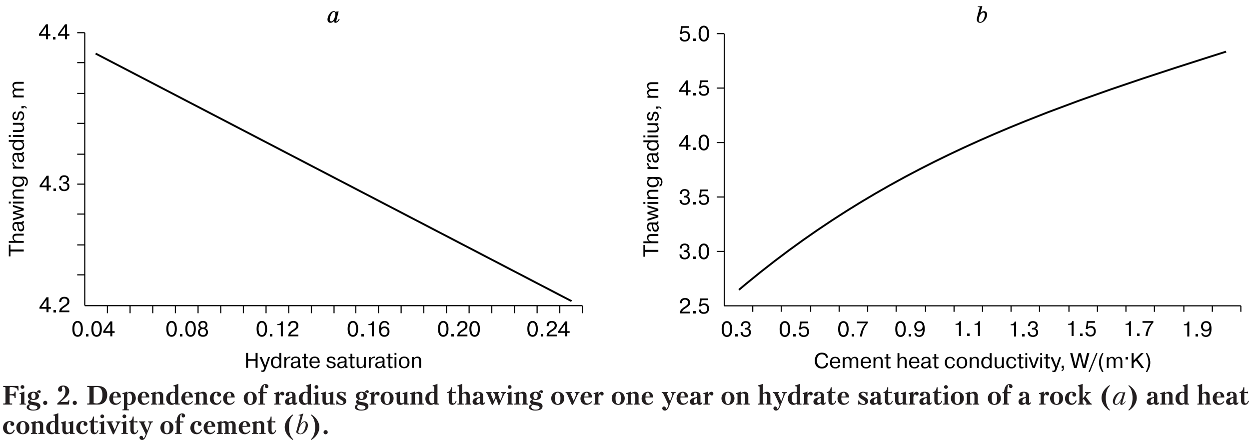

Fig. 2. Dependence of radius ground thawing over one year on hydrate saturation of a rock (*a*) and heat conductivity of cement (*b*).

ence of the borehole equaled to 10.2 m. At the expense of hydrate decomposition at depth $H = 100$ m during the first year of operations, the well produced ca. 63 600 m^3 of gas under normal conditions, with the gas volume calculated according to the formula

$$V_g = \pi R_*^2 H m \rho_{0g} s_{h0} \cdot 22.4/16.$$

Over the entire period of the field development (e.g., 30 years), the thawing radius was found to have reached 23.5 m. This may have dramatic consequences for the stability of wells.

Fig. 2, *a* represents a dependence diagram for the growth of thaw halo radius within one year and saturation of rocks with hydrate, with the sum of ice content and hydrate saturation remaining constant. Fig. 2, *b* shows the dynamics of the formation of thawing radius during one year versus thermal conductivity of cement. In cases when thermal conductivity of cement was brought down to 0.4 W/(m·K), the thawing radius was thereby lowered down to 3 m during a year. For one more example, mass fractions of microspheres less than 25 % can lower the thermal conductivity value of cement sheath [*Korostelev, 2011*].

CONCLUSIONS

The novel contribution of this work is the mathematical model for thermal interaction between the producing well and the permafrost strata holding relic metastable hydrates. The dynamics of temperature distribution in thawed and frozen zones and analytical dependence for defining the phase boundary were also obtained from the model.

The developed thereby formula for the radius of well's thermal influence propagation has shown that the radial distribution of the thawing affect is controlled by the difference between the initial and phase transition temperatures, by the rate of the phase transition front movement, and temperature conductivity of the frozen zone.

The resulting calculation data indicate that even low values of hydrate saturation of the permafrost strata can lead to essential changes in the thermal characteristics, and that upon thawing, these hydrates may yield considerable volumes of gas.

As part of the self-similar solutions, we analyzed the influence of hydrate saturation of rocks and thermal conductivity of the cement sheath on the radius of soil thawing around the borehole.

The use of thermal insulation materials allows reducing not only the thaw halo radius, but also the risk of massive gas liberations during the construction of a well. Preparation of the cement slurry with low heat development while hardening and low thermal conductivity is another obvious direction that might be pursued for improvements of the Arctic-specific technologies for oil and gas production, and for ensuring the rational use of subsoil.

The performed calculations substantiated a necessity in the development of technology solutions to provide for the adequate environmental management under the permafrost conditions throughout the entire oil and gas field development cycle.

The research was financially supported by the Russian Ministry for Education and carried out within the framework of the state-commissioned project in the field of scientific activity (No. 13.290.2014/K).

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Received March 26, 2015