DOI 10.1007/s10891-015-1284-5
Journal of Engineering Physics and Thermophysics, Vol. 88, No. 5, September, 2015

FEATURES OF THE DECOMPOSITION OF GAS HYDRATES WITH THE FORMATION OF ICE IN A POROUS MEDIUM

M. K. Khasanov,[a] **N. G. Musakaev,**[b] **and I. K. Gimaltdinov**[a]

UDC 532.546:536.421

We have investigated the features of the decomposition of gas hydrates into the gas and ice in the process of gas extraction from a porous medium saturated with the gas and the gas hydrate in the initial state. We have obtained self-similar solutions of this problem in an axisymmetric formulation describing the distributions of the main parameters in the stratum upon decomposition of the gas hydrate in an extended region. Critical diagrams of existence of the above solution have been constructed. It has been shown that in the case of a negative temperature of the stratum in the initial state (T_0 < 273.15 K), the gas hydrate will always decompose into the gas and ice. At a positive initial temperature of the stratum (T_0 > 273.15 K), the gas hydrate can decompose depending on the initial parameters of the system and the intensity of extraction of the gas with the formation of both water and ice.

Keywords: *gas hydrate decomposition, self-similar solution, porous medium.*

Introduction. Gas hydrates represent crystalline compounds formed from the gas and water under certain thermobaric conditions. Underground deposits of this alternative source of hydrocarbon raw materials are gaining in importance in connection with the continued exhaustion of the traditional oil and gas deposits and increasing prices for the main energy carriers [1, 2]. Therefore, the necessity arises to develop effective and safe technologies of extracting the gas from gas hydrate deposits.

Extracting carbohydrate raw materials from gas-hydrate deposits is a highly complicated problem requiring a thorough and comprehensive theoretical study [3]. The conventional methods of extracting natural gas from such deposits include the action of heat and/or a low pressure on the gas hydrates causing their decomposition into the gas and water (in most case) or the gas and ice.

In [3–8], mathematical models of the process of decomposition of the gas hydrates were proposed. In [3, 4], in particular, it was pointed out that decomposition conditions at negative temperatures are possible. If the hydrate is decomposed not into the gas and water but into the gas and ice, then it permits decreasing energy expenditures in exploit gas-hydrate deposits, since the specific heat of the hydrate–ice phase transition is much lower than the heat of the hydrate–water phase transition, i.e., the decomposition of the hydrate into the gas and ice is an energetically more efficient procedure.

Unlike [3–6, 8], where the mathematical model of the process of decomposition of the hydrate into the gas and water was proposed in a linear-parallel formulation, in the present paper we have constructed an analytical solution of the axisymmetrical problem on the decomposition of the gas hydrate in a porous medium into the gas and ice in the process of gas extraction from a hydrate-containing stratum which can have in the initial state both a negative (T_0 < 273.15 K) and a positive temperature. Moreover, in [3–6, 8] solutions were obtained for the case of phase transitions on the frontal surface, which gives an adequate mathematical description only for a limited range of parameters characterizing the state of the system and the intensity of action on the stratum, namely at a low gas extraction intensity and a low permeability of porous media. In the present paper, we have constructed a mathematical model of the gas hydrate decomposition with the formation of a volume region of phase transitions that permits investigating the features of the process of gas hydrate decomposition at a high intensity of gas extraction.

Formulation of the Problem and Basic Equations. Let us be given a horizontal porous stratum saturated in the initial state with a gas or a gas hydrate. The gas (methane) is extracted through a well perforated through the whole thickness of the stratum.

---

[a]Sterlitamak Branch of the Bashkir State University, 37 Lenin Ave., Sterlitamak, 453103, Bashkortostan, Russia; email: hasanovmk@mail.ru; [b]Tyumen′ Branch of the Institute of Theoretical and Applied Mechanics, Siberian Branch of the Russian Academy of Sciences, 74 Taimyrskaya Str., Tyumen′, 625026, Russia; email: musakaev@ikz.ru. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 88, No. 5, pp. 1022–1030, September–October, 2015. Original article submitted June 30, 2014.

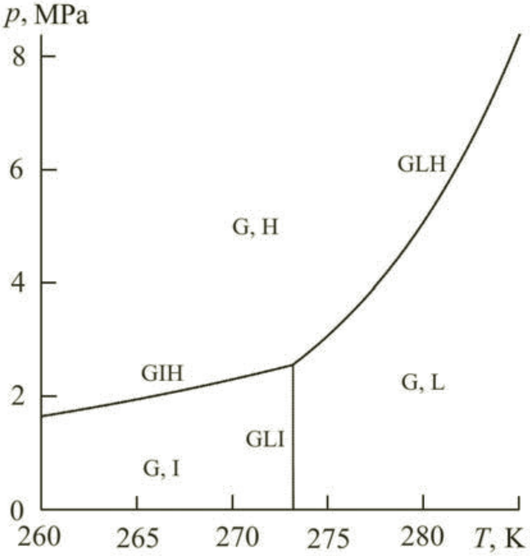

Fig. 1. Phase diagram of the H_2O–CH_4 system.

To describe the heat and mass transfer processes during gas extraction, let us make the following assumptions:

the process proceeds at a single temperature, i.e., the temperatures of the porous medium and the saturating substance (gas, hydrate, water, or ice) coincide;

the hydrate is a two-components system with a mass concentration of the gas G;

the skeleton of the porous medium, the gas hydrate, the water and ice are incompressible and stationary;

the porosity of the gas hydrate is constant, and the gas is calorically perfect.

The system of basic equations describing the processes of filtration and heat transfer when the gas hydrate is decomposed in a porous medium represents the mass and energy conservation laws, the Darcy law, and the equation of state for the gas. Under the assumptions made in the axisymmetrical case, the basic equations will have the following form [9, 10]:

$$\frac{\partial}{\partial t}\left(\rho_{\mathrm{g}} m S_{\mathrm{g}} + \rho_{\mathrm{h}} m S_{\mathrm{h}} G\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r S_{\mathrm{g}} m \upsilon_{\mathrm{g}} \rho_{\mathrm{g}}\right) = 0 ,$$

$$\frac{\partial}{\partial t}\left(m \rho_{\mathrm{i}} S_{\mathrm{i}} + m\left(1 - G\right)\rho_{\mathrm{h}} S_{\mathrm{h}}\right) = 0 , \qquad (1)$$

$$\frac{\partial}{\partial t}\left(\rho c T\right) + \rho_{\mathrm{g}} c_{\mathrm{g}} m S_{\mathrm{g}} \upsilon_{\mathrm{g}} \frac{\partial T}{\partial r} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial t}\left(m \rho_{\mathrm{h}} S_{\mathrm{h}} L_{\mathrm{h}}\right) ,$$

$$m S_{\mathrm{g}} \upsilon_{\mathrm{g}} = -\frac{k_{\mathrm{g}}}{\mu_{\mathrm{g}}}\frac{\partial p}{\partial r} , \quad p = \rho_{\mathrm{g}} R_{\mathrm{g}} T ,$$

where G is the mass concentration of the gas in the hydrate, ρ_j and S_j (j = h, i, g, liq) are the true density and saturation of the pores of the jth phase, and ρc is the volume heat capacity of the system. The coordinate r is counted off from the control axis of the well.

In the case of decomposition of the gas hydrate into the gas and water, we will consider the latter to be stagnant, since at low values of the hydrate-saturation (and, accordingly, of the water-saturation), as the estimate made by us [10, 11] show, the assumption of stagnancy of the liquid is quite justified. In our calculations, the initial hydrate-saturation of the stratum will not exceed 0.2. The dependence of the permeability coefficient for the gas-saturation can be determined on the basis of the Kozeni formula

$$k_{\mathrm{g}} = k_* \frac{(m S_{\mathrm{g}})^3}{(1 - m S_{\mathrm{g}})^2} \approx k_0 S_{\mathrm{g}}^3 \left(k_0 = k_* m^3\right) .$$

The values of the temperature and pressure in the region of decomposition of the hydrate are related by the phase equilibrium condition

$$T_s(p) = T_0 + T_* \ln\left(p/p_{s0}\right), \tag{2}$$

where T_0 is the initial temperature of the system, p_{s0} is the equilibrium pressure corresponding to the temperature T_0, and T_* is the empirical parameter depending on the kind of gas hydrate and the phase into which it decomposes (in the case of decomposition of the hydrate into the gas and ice, the value of the parameter T_* is three times higher than in the case of decomposition into the gas and water).

The phase diagram for the H_2O–CH_4 system is given in Fig. 1. In this diagram, the GLH, GIH, and GLI curves define the three-phase equilibrium of methane–water–hydrate, methane–ice–hydrate, and methane–water–ice, respectively. The GIH and GLH lines correspond to the equilibrium parameters of the gas hydrate decomposition with the formation of ice and water, respectively.

When the gas hydrate decomposes into the gas and ice, zones arise in the porous stratum, in which the gas, the ice, and the hydrate can be present in different ratios. On the discontinuity surfaces between these zones, where the phase saturation jumps as well as the mass and heat flows undergo drastic changes, the relations following from the mass and heat balance conditions hold:

$$m\left(S_h\rho_h(1-G) + S_i\rho_i\right)\dot{r}_{(j)} = 0,$$

$$m\left(\rho_g S_g(\upsilon_g - \dot{r}_{(j)}) - \rho_h S_h G\dot{r}_{(j)}\right) = 0, \tag{3}$$

$$\lambda\frac{\partial T}{\partial r} = m\rho_h L_h S_h \dot{r}_{(j)}.$$

Here $\dot{r}_{(j)}$ is the boundary velocity $r = r_{(j)}$ ($j = n$ for the near boundary of phase transitions, $j = d$ for the far boundary of phase transitions). The temperature and pressure at this boundary are assumed to be continuous.

In the case of decomposition of the gas hydrate into the gas and water, the first equation of system (3) takes on the form

$$m\left(S_h\rho_h(1-G) + S_{liq}\rho_{liq}\right)\dot{r}_{(n)} = 0.$$

Let us assume that the stratum at the initial instant of time is saturated with the gas and the gas hydrate, whose pressure p_0 and temperature T_0 in the initial state agree with the conditions of their existence in the free state ($p_0 > p_{s0}$). Let the pressure and temperature be initially ($t = 0$) equal throughout the stratum: $T = T_0$ and $p = p_0$ ($r > r_w$) and through the well perforated in the stratum throughout its depth the gas be extracted at a constant mass flow rate Q (per unit height of the well) under the condition of absence of conductive heat flux at the well boundary. As a result of the operation of the well, because of the pressure drop to below the equilibrium pressure, decomposition of the hydrate occurs, and in the stratum three characteristic zones arise: a near (first) zone where the pores are filled with the gas and ice (water), an intermediate (second) zone in which the gas, ice (water), and the hydrate are at equilibrium, and a far (third) zone saturated with the gas and the hydrate. In the second zone, decomposition of the hydrate occurs, which leads to the appearance of two moving surfaces — between the far and the intermediate zones, where the hydrate begins to melt, and between the near and the intermediate zones, where the process of its decomposition reaches completion. The initial hydrate-saturation of the stratum ν is equal to the hydrate-saturated third zone and is constant at all points of this zone.

If we assume that on fairly large times after the beginning of gas extraction, when the radius of the near (first) zone is much larger than the radius of the well r_w, the size of the well weakly influences the character of the process, then, in view of the Darcy law and the equation of state for the gas, the conditions at the well boundary ($r = r_w$) can be written in the following form:

$$\frac{k_g\pi}{\mu_g R_g T}\left(r\frac{\partial p^2}{\partial r}\right) = Q, \quad \frac{\partial T}{\partial r} = 0\left(r_w \to 0,\ t > 0\right).$$

Note that the process of decomposition of the gas hydrate, generally speaking, is accompanied by nonequilibrium processes. However, the given mathematical model ignores the kinetics of the process, since the characteristic nonequilibrium relaxation times are, as a rule, short compared to the time intervals that are of interest in the problem under consideration

[9, 10]. Therefore, the proposed mathematical model with an equilibrium scheme holds for the limiting case where, because of the rather large time scales of the process, it is limited not by its kinetics, but by the heat transfer in a porous medium [10, 11].

Self-Similar Solutions. Let us introduce the self-similar variable $\xi = r/\sqrt{\chi^{(T)}t}$, where $\chi^{(T)} = \lambda/\rho c$ is the thermal diffusivity of the stratum. Because the phases are stagnant and the difference in density between the methane hydrate and the ice is minor, the change in the gas-saturation and, therefore, in the permeability due to the decomposition of the gas hydrate can be neglected. Then, in view of (1) and (2), the piezoconduction and thermal diffusivity equations can be written in the following form:

$$-\xi\,\frac{dp^2}{d\xi} = \frac{2\chi^{(p)}}{\chi^{(T)}}\,\frac{1}{\xi}\,\frac{d}{d\xi}\left(\xi\,\frac{dp^2}{d\xi}\right) + 2\varphi_{\mathrm{h}}\,p^2\xi\,\frac{dS_{\mathrm{h}}}{d\xi}\,,$$

$$-\xi\,\frac{dT}{d\xi} = \frac{\mathrm{Pe}}{p_0^2}\,\frac{dp^2}{d\xi}\,\frac{dT}{d\xi} + \frac{2}{\xi}\,\frac{d}{d\xi}\left(\xi\,\frac{dT}{d\xi}\right) - \Delta T\,\xi\,\frac{dS_{\mathrm{h}}}{d\xi}\,,$$

where $\chi^{(p)} = \dfrac{k_{\mathrm{g}}p}{mS_{\mathrm{g}}\mu_{\mathrm{g}}}$, $\mathrm{Pe} = \dfrac{\rho_{\mathrm{g}0}c_{\mathrm{g}}k_{\mathrm{g}}p_0}{\lambda\mu_{\mathrm{g}}}$, $\varphi_{\mathrm{h}} = \dfrac{\rho_{\mathrm{h}}G}{\rho_{\mathrm{g}0}(1-\nu)}$, $\Delta T = \dfrac{m\rho_{\mathrm{h}}L_{\mathrm{h}}}{\rho c}$, and $\rho_{\mathrm{g}0}$ is the gas density at pressure p_0. Here the piezoconduction equation is nonlinear, since the piezoconductivity coefficient $\chi^{(p)}$ contains the unknown function p. To obtain an approximate analytical solution, let us make use of the Leibenzon linearization method [12], i.e., let us assume that the variable pressure p in the piezoconductivity coefficient $\chi^{(p)}$ is constant and equal to the initial pressure p_0.

Analysis shows that in the majority of cases of practical interest, in the heat inflow equation for the intermediate zone the term responsible for convection can be neglected. Then, taking into account that in the near and far zones the hydrate-saturation S_{h} has a constant value, the solutions for the pressure and temperature distribution on each of the zones will take the following form upon integration:

the near zone ($0 < \xi < \xi_{(n)}$)

$$p_{(1)}^2 = p_{(n)}^2 - \frac{Q\mu_{\mathrm{g}}R_{\mathrm{g}}T_{\mathrm{w}}}{\pi k_{(1)}}\int_{\xi}^{\xi_{(n)}}\frac{1}{\xi}\exp\left(-\frac{\xi^2}{4\eta_{(1)}}\right)d\xi\,,$$

$$T_{(1)} = T_{(n)},\quad S_{\mathrm{h}(1)} = 0\,; \qquad (4)$$

the intermediate zone ($\xi_{(n)} < \xi < \xi_{(d)}$)

$$p_{(2)}^2 = p_{(d)}^2 + \left(p_{(n)}^2 - p_{(d)}^2\right)\frac{\displaystyle\int_{\xi}^{\xi_{(d)}}\frac{1}{\xi}\exp\left(-\frac{\xi^2}{4\tilde{\eta}_{(2)}}\right)d\xi}{\displaystyle\int_{\xi_{(n)}}^{\xi_{(d)}}\frac{1}{\xi}\exp\left(-\frac{\xi^2}{4\tilde{\eta}_{(2)}}\right)d\xi}\,,$$

$$T_{(2)} = T_0 + T_*\ln\left(p_{(2)}/p_{\mathrm{s}0}\right),\quad S_{\mathrm{h}(2)} = \nu - \frac{T_*(\eta_{(2)}-1)}{2(\varphi_{\mathrm{h}}\,T_* + \eta_{(2)}\,\Delta T)}\ln\frac{p_{(d)}^2}{p_{(2)}^2}\,; \qquad (5)$$

the far zone ($\xi_{(d)} < \xi < \infty$)

$$p_{(3)}^2 = p_0^2 + \frac{\left(p_{(d)}^2 - p_0^2\right)\displaystyle\int_{\xi}^{\infty}\frac{1}{\xi}\exp\left(-\frac{\xi^2}{4\eta_{(3)}}\right)d\xi}{\displaystyle\int_{\xi_{(d)}}^{\infty}\frac{1}{\xi}\exp\left(-\frac{\xi^2}{4\eta_{(3)}}\right)d\xi}\,,$$

$$T_{(3)} = T_0 + \frac{\left(T_{(d)} - T_0\right) \int\limits_{\xi}^{\infty} \frac{1}{\xi} \exp\left(-\frac{\xi^2}{4} - \frac{\mathrm{Pe}_{(3)}}{2p_0^2}\, p_{(3)}^2\right) d\xi}{\int\limits_{\xi_{(d)}}^{\infty} \frac{1}{\xi} \exp\left(-\frac{\xi^2}{4} - \frac{\mathrm{Pe}_{(3)}}{2p_0^2}\, p_{(3)}^2\right) d\xi}, \tag{6}$$

$$S_{\mathrm{h}(3)} = \nu\,.$$

Here $\eta_{(j)} = \dfrac{\chi_{(j)}^{(p)}}{\chi^{(T)}}$, $\chi_{(j)}^{(p)} = \dfrac{k_{(j)} p_0}{m S_{\mathrm{g}(j)} \mu_{\mathrm{g}}}$, $\tilde{\eta}_{(2)} = \dfrac{\varphi_{\mathrm{h}} T_* + \eta_{(2)} \Delta T}{\varphi_{\mathrm{h}} T_* + \Delta T}$, $k_{(j)} = k_0 S_{\mathrm{g}(j)}^3$.

On the surface separating the near and the intermediate zones (at the first boundary), the hydrate-saturation changes suddenly from $S_{\mathrm{h}}^- = 0$ to $S_{\mathrm{h}}^+ = S_{\mathrm{h}(n)}$. On the basis of relation (3) in view of solutions (4) and (5) and the phase equilibrium condition (2), the relations for determining the coordinates of the first boundary $\xi_{(n)}$ and the values of parameters on it can be written:

$$\frac{Q \mu_{\mathrm{g}} R_{\mathrm{g}} T_{\mathrm{w}}}{\pi} \exp\left(-\frac{\xi_{(n)}^2}{4\eta_{(1)}}\right) - k_{(2)} \frac{p_0^2 - p_{(n)}^2}{\int\limits_{\xi_{(n)}}^{\infty} \frac{1}{\xi} \exp\left(-\frac{\xi^2}{4\eta_{(2)}}\right) d\xi} \exp\left(-\frac{\xi_{(n)}^2}{4\eta_{(2)}}\right) = K S_{\mathrm{h}(n)}\, \xi_{(n)}^2\,,$$

$$\frac{\left(T_0 - T_{(n)}\right) \exp\left(-\frac{\xi_{(n)}^2}{4} - \frac{\mathrm{Pe}_{(2)}}{2p_0^2}\, p_{(n)}^2\right)}{\int\limits_{\xi_{(n)}}^{\infty} \frac{1}{\xi} \exp\left(-\frac{\xi^2}{4} - \frac{\mathrm{Pe}_{(2)}}{2p_0^2}\, p_{(2)}^2\right) d\xi} = \frac{\Delta T S_{\mathrm{h}(n)}}{2}\, \xi_{(n)}^2\,, \tag{7}$$

where $K = m \mu_{\mathrm{g}} \chi^{(T)} p_0 \left(\dfrac{\rho_{\mathrm{h}} G}{\rho_{\mathrm{g}0}} + \dfrac{\rho_{\mathrm{h}}(1 - G)}{\rho_{\mathrm{i}}} - 1\right)$.

On the surface separating the far and the intermediate zones (at the second boundary), we assume that the hydrate-saturation $S_{\mathrm{h}(d)}$ value is continuous and equal to the initial hydrate-saturation. Then on the basis of relations (3) in view of solutions (5) and (6) and the phase equilibrium condition (2), we obtain the equations for determining the coordinates of the second boundary $\xi_{(d)}$ and the values of parameters on it:

$$\frac{\left(p_{(d)}^2 - p_{(n)}^2\right) \exp\left(-\frac{\xi_{(d)}^2}{4\chi}\right)}{\int\limits_{\xi_{(n)}}^{\xi_{(d)}} \frac{1}{\xi} \exp\left(-\frac{\xi^2}{4\chi}\right) d\xi} = \frac{\left(p_0^2 - p_{(d)}^2\right) \exp\left(-\frac{\xi_{(d)}^2}{4\eta_{(3)}}\right)}{\int\limits_{\xi_{(d)}}^{\infty} \frac{1}{\xi} \exp\left(-\frac{\xi^2}{4\eta_{(3)}}\right)},$$

$$\frac{T_*}{2p_{(d)}^2} \frac{\left(p_{(d)}^2 - p_{(n)}^2\right) \exp\left(-\frac{\xi_{(d)}^2}{4\chi}\right)}{\int\limits_{\xi_{(n)}}^{\xi_{(d)}} \frac{1}{\xi} \exp\left(-\frac{\xi^2}{4\chi}\right) d\xi} = \frac{\left(T_0 - T_{(d)}\right) \exp\left(-\frac{\xi_{(d)}^2}{4} - \frac{\mathrm{Pe}_{(3)}}{2p_0^2}\, p_{(d)}^2\right)}{\int\limits_{\xi_{(d)}}^{\infty} \frac{1}{\xi} \exp\left(-\frac{\xi^2}{4} - \frac{\mathrm{Pe}_{(3)}}{2p_0^2}\, p_{(3)}^2\right) d\xi}. \tag{8}$$

At these boundaries the temperature values are related thereby by the phase equilibrium condition

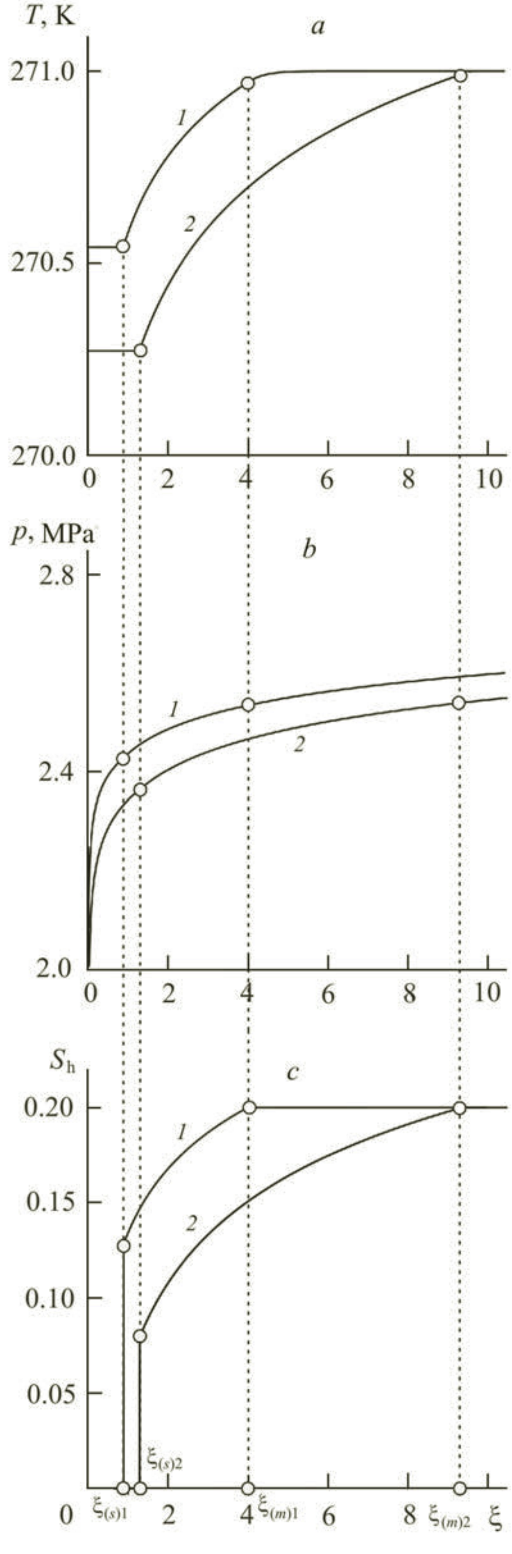

Fig. 2. Distribution of the temperature (a), pressure (b), and hydrate-saturation (c) of the stratum along the ξ axis in the process of gas hydrate decomposition into the gas and ice at $Q = 0.004$ (1) and 0.005 kg/(m·s) (2).

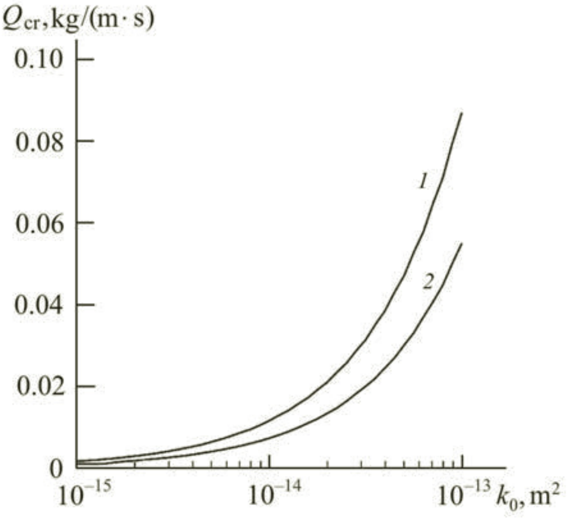

Fig. 3. Critical values of the mass flow rate versus the absolute permeability of the stratum at its initial temperatures $T_0 = 268$ (1) and 272 K (2).

$$T_{(n)} = T_0 + T_* \ln\left(p_{(n)}/p_{s0}\right), \quad T_{(d)} = T_0 + T_* \ln\left(p_{(d)}/p_{s0}\right).$$

From (5) we find the hydrate-saturation value at the first boundary (on the side of the second zone):

$$S_{h(n)} = \nu - \frac{T_*\left(\eta_{(2)} - 1\right)}{2\left(\Delta T \eta_{(2)} + \varphi_h T_*\right)} \ln \frac{p_{(d)}^2}{p_{(n)}^2}.$$

From Eqs. (7) and (8) the parameter values at the boundaries between the zones are determined numerically, and on the basis of solutions (4)–(6) the distributions of parameters in each zone are found.

Results of the Calculations. Figure 2 gives the temperature, pressure, and hydrate-saturation distributions for various values of the mass flow rate of methane in the process of its extraction from the hydrate-containing stratum. These distributions were obtained for a negative initial temperature of the stratum ($T_0 < 273.15$ K) and correspond to the hydrate decomposition into the gas and ice. For the parameters characterizing the system, the following values are taken: $m = 0.1$, $G = 0.12$, $\nu = 0.2$, $p_0 = 2.8$ MPa, $T_0 = 270$ K, $T_* = 30$ K, $p_{s0} = 2.54$ MPa, $R_g = 520$ J/(K·kg), $k_0 = 10^{-14}$ m^2, $\rho_h = \rho_i = 900$ kg/m^3, $\rho c = 2.5 \cdot 10^6$ J/(K·kg), $c_g = 1560$ J/(K·kg), $\lambda = 2$ W/(m·K), $\mu_g = 10^{-5}$ kg/(m·s), $L_h = 1.66 \cdot 10^5$ J/kg.

From Fig. 2 it is seen that the temperature in the three-phase region decreases to below the initial temperature of the stratum, which is due to the absorption of the latent heat of the phase transition. Consequently, in the case of a negative initial temperature of the stratum, the gas hydrate will always decompose into the gas and ice. Moreover, as is seen from Fig. 2, a decrease in the mass flow rate of the gas extracted from the stratum decreases the length of the intermediate zone and the portion of the hydrate decomposed in this zone. Thus, with decreasing value of the mass flow rate of the gas in the process of its extraction, the scheme of the process becomes closer and closer to the scheme used in [3–5, 8] with the frontal surface of hydrate decomposition.

Let us estimate the characteristic operating times of the well t_* at which the radius of the near (first) zone $r_{(s)}$ exceeds considerably the radius of the well r_w and, accordingly, the size of the well has a weak effect on the features of the process of decomposition of the gas hydrate into components. The value of $r_{(s)}$ can be determined from the relation $r_{(n)} = \xi_{(n)}\sqrt{\chi^{(T)}t}$. Then we have the condition

$$\xi_{(n)}\sqrt{\chi^{(T)}t_*} >> r_w$$

or the condition

$$t_* >> r_w^2/\chi^{(T)}\xi_{(n)}^2.$$

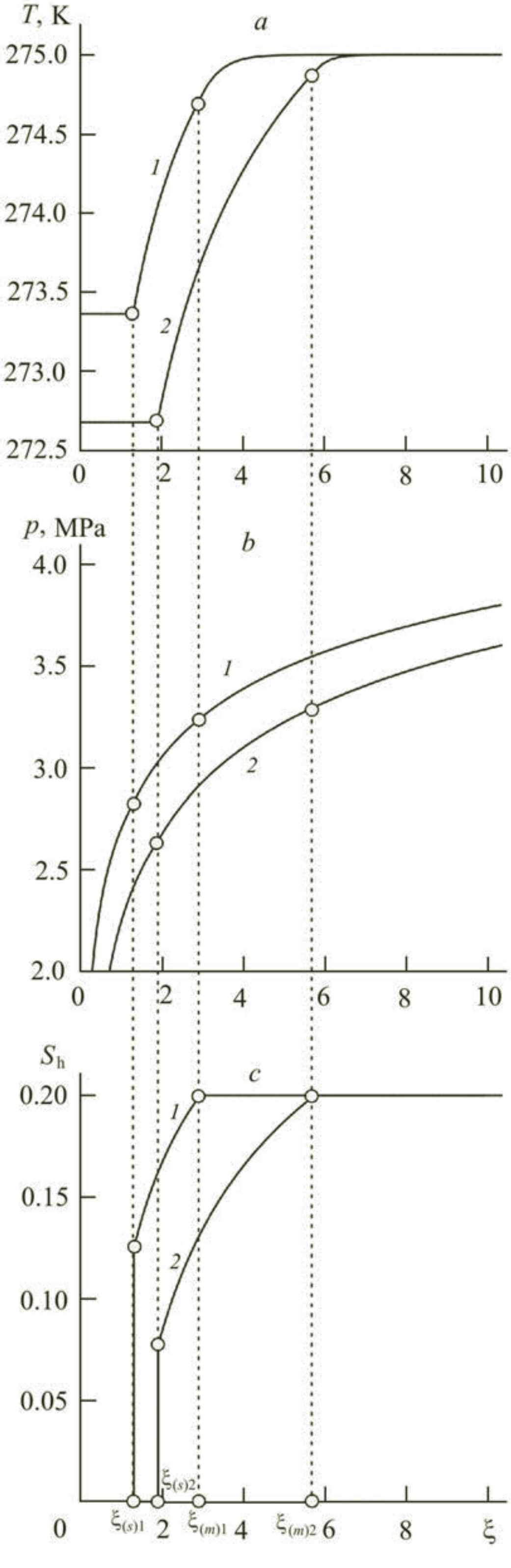

Fig. 4. Distribution of the temperature (a), pressure (b), and hydrate-saturation (c) of the stratum along the variable ξ in the case of gas hydrate decomposition into the gas and water at $Q = 0.035$ (1) and 0.045 kg/(m·s) (2).

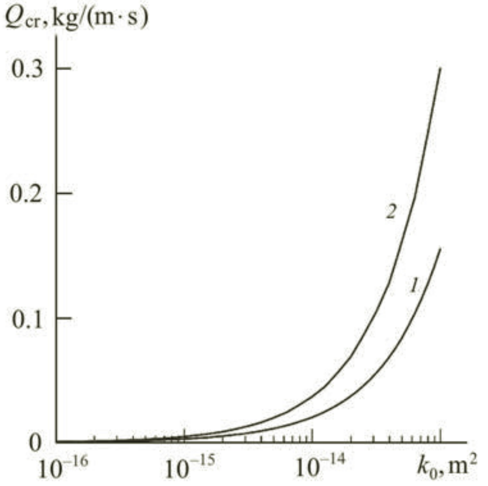

Fig. 5. Critical value of the mass flow rate versus the absolute permeability of the stratum having in the initial state a positive temperature at $T_0 = 275$ K and $p_0 = 5$ MPa.

At parameter values corresponding to the distributions in Fig. 2, assuming that the well radius $r_w = 0.1$ m, we get $t_* >> 1.25 \cdot 10^4$ s. Thus, the size of the well has a weak effect on the features of the process at characteristic operating times of the well of the order of a few hours or more.

We have performed computing experiments for a wide range of parameters with the aim of determining such a value of the quantity of extracted gas Q_{cr} (let us call it critical) that at lower values of the mass flow rate the extended region of hydrate decomposition degenerates into a frontal surface. It has been established by means of calculations that the main parameters influencing the Q_{cr} value are the permeability of the stratum, as well as the pressure p_0 and temperature T_0 in it.

Figure 3 shows the dependences of the quantity Q_{cr} on the absolute permeability of the stratum at various values of the initial temperature in it in the case of extraction from a stratum with the initial pressure $p_0 = 3$ MPa. It is seen that with increasing permeability the critical value of the mass flow rate increases, and the lower the initial temperature of the stratum, the higher the increase rate. Thus, at a fixed mass flow rate of the gas in the process of its extraction the frontal regime is realized in highly permeable porous media, as well as in strata with a low initial stratum temperature, i.e., in strata whose initial state is far from the decomposition condition of the gas hydrate. This is explained by the fact that the decrease in the permeability of the stratum at a fixed mass flow rate of the gas in the process of its extraction determines the main pressure drop in the immediate vicinity of the well (i.e., in a relatively narrow near region), thus leading to a decrease in the pressure $p_{(s)}$ at the boundary between the first and the second regions. In accordance with Fig. 2, to the regime of the volume region of hydrate decomposition there correspond rather low values of the pressure $p_{(n)}$ and the temperature $T_{(n)}$ at this boundary compared to the initial values of p_0 and T_0.

Thus, for the mass flow rate of extracted gas there exists some minimal value depending on the permeability, the initial temperature, and the initial pressure of the stratum, such that at a mass flow rate below this value the volume region of hydrate decomposition degenerates into the frontal surface of the phase transitions. The possibility of two kinds of solutions of the hydrate decomposition problem was noted in monograph [3], but this fact was established there as a result of the analysis of the rectilinear-parallel problem with a frontal surface of phase transitions.

Figure 4 shows graphs for the case of a positive initial temperature of the stratum ($T_0 > 273.15$ K) and decomposition of the hydrate into the gas and water. It was assumed that in the intermediate region the gas, the hydrate, and the water are in the phase equilibrium state and that the initial state of the system is characterized by the following parameters: $p_0 = 50$ MPa, $T_0 = 275$ K, $T_* = 10$ K, $p_{s0} = 3.3$ MPa, $L_h = 5 \cdot 10^5$ J/kg. From Fig. 4 it is seen that if the mass flow rate of the extracted gas is fairly high (curve 2), then the temperature at the boundary separating the first and the second regions decreases to below the freezing temperature of water, which corresponds to its "supercooling." Consequently, in this case a model with two moving interfaces does not permit constructing a physically noncontradictory solution. To avoid this contradiction, it is necessary to introduce into consideration the third interface at which ice is formed and, accordingly, the fourth additional region where the gas, the ice, and the water coexist simultaneously in the equilibrium state.

Figure 5 shows for the case of a positive initial temperature of the stratum the dependence of the critical mass flow rate of the gas in the process of its extraction on the absolute permeability of the stratum determining the appearance in it of an extended region of hydrate decomposition into the gas and water (curve 1) and two extended regions of hydrate decomposition into both the gas and water and the gas and ice (curve 2). The two curves in Fig. 5 divide the plane (k_0, Q) into three regions corresponding to different regimes of hydrate decomposition. In the region under the first curve, there exists a noncontradictory solution with a frontal surface of hydrate decomposition into the gas and water. The region between curves 1 and 2 corresponds to the gas hydrate decomposition in the extended region with liberation of the gas and water. The region above curve 2 corresponds to the formation of two extended regions of phase transitions with gas hydrate decomposition into both gas and water and into gas and ice. As is seen from Fig. 5, the regime with the formation of ice is characteristic of low-permeability porous media. This is due to the fact that a decrease in the stratum permeability at a fixed mass flow rate of the gas in the process of its extraction leads to a considerable decrease in the pressure in the immediate vicinity of the well, thus leading to a decrease in the pressure and, accordingly, in the temperature at the hydrate decomposition boundary, and the temperature becomes lower than the freezing temperature of water.

Conclusions. The process of gas hydrate decomposition into ice and the gas in a porous stratum has been investigated. It has been shown that in the case of a negative initial temperature of the stratum the gas hydrate decomposition always occurs with the formation of ice either on the frontal surface or in the extended region. In the case of a positive initial temperature of the stratum, depending on the rate of gas extraction and the initial parameters of the system, the gas hydrate decomposition can occur either on the frontal surface (into the gas and water) or in one extended region with the liberation of the gas and water, or in two extended regions (both into the gas and water and into the gas and ice).

This work was supported by the Russian Foundation for Basic Research (project 14-01-31089).

NOTATION

c, specific heat capacity, J/(K·kg); *d*, boundary between the intermediate and the near regions; *k*, permeability coefficient, m^2; L_h, specific heat of the phase transition, J/kg; *m*, porosity; *n*, boundary between the near and the intermediate regions; *p*, pressure, Pa; *Q*, mass flow rate referred to a unit height of the well, kg/(m·s); *r*, coordinate, m; R_g, gas constant, J/(K·kg); *S*, saturation; *t*, time, s; *T*, temperature, K; λ, heat conductivity coefficient, W/(m·K); μ, dynamic viscosity coefficient, kg/(m·s); ξ, dimensionless self-similar variable; ρ, density, kg/(m·s); υ, velocity, m/s. Subscripts: cr, critical; g, gas phase; h, hydrate; i, ice; liq, liquid phase; s, solid phase; w, well; 0, initial state; 1, 2, 3, values of parameters corresponding to regions 1, 2, and 3.

REFERENCES

1. S. Sh. Byk, Yu. F. Makogon, and V. I. Fomina, *Gas Hydrates* [in Russian], Khimiya, Moscow (1980).
2. V. A. Istomin and V. S. Yakushev, *Gas Hydrates under Natural Conditions* [in Russian], Nedra, Moscow (1992).
3. G. G. Tsypkin, *Flows with Phase Transitions in Porous Media* [in Russian], Fizmatlit, Moscow (2009).
4. G. G. Tsypkin, Mathematical model of the dissociation of gas hydrates coexisting with the gas in strata, *Dokl. Ross. Akad. Nauk*, **381**, No. 1, 56–59 (2001).
5. V. I. Vasil′ev, V. V. Popov, and G. G. Tsypkin, Numerical investigation of the dissociation of gas hydrates coexisting with the gas in natural strata, *Izv. Ross. Akad. Nauk*, *Mekh. Zhidk. Gaza*, No. 4, 127–134 (2006).
6. G. G. Tsypkin, Gas hydrate dissociation regimes in highly permeable beds, *J. Eng. Phys. Thermophys*., **63**, No. 6, 1221–127 (1992).
7. V. Sh. Shagapov, M. K. Khasanov, I. K. Gimaltdinov, and M. V. Stolpovskii, Features of the dissociation of gas hydrates in porous media under warm gas injection, *Teplofiz. Aéromekh*., **20**, No. 3, 347–354 (2013).
8. G. G. Tsypkin, Regimes of dissociation of gas hydrates co-existing with the gas in natural strata, *J. Eng. Phys. Thermophys*., **74**, No. 5, 1073–1082 (2001).
9. R. I. Nigmatulin, *Dynamics of Multiphase Media* [in Russian], Nauka, Moscow (1987).
10. V. Sh. Shagapov, M. K. Khasanov, and N. G. Musakaev, Formation of gas hydrates in a porous reservoir partially saturated with water by cold gas injection, *Prikl. Mekh. Tekh. Fiz*., **49**, No. 3, 462–472 (2008).
11. M. K. Khasanov, I. K. Gimaltdinov, and M. V. Stolpovskii, Features of the formation of gas hydrates by cold gas injection into a porous medium saturated with a gas and water, *Teor. Osn. Khim. Tekhnol*., **44**, No. 4, 442–449 (2010).
12. K. S. Basniev, I. N. Kochina, and V. M. Maksimov, *Underground Hydromechanics* [in Russian], Nedra, Moscow (1993).