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POSSIBILITY OF GAS WASHOUT FROM A GAS-HYDRATE MASSIF BY CIRCULATION OF WARM WATER

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A possibility of gas extraction from a gas-hydrate massif by means of warm water circulation through a system of wells is demonstrated. A technological scheme and a theoretical model of this process are proposed.

Key words: *gas-hydrate massif, heat-carrying agent, well, gas production.*

Introduction. Modern geological surveys predict that bottom sediments in seas and oceans contain large amounts of hydrocarbon gases in the form of solid gas-hydrate deposits (approximately 98% of gas hydrates are located in the ocean, and only 2% are located on land in permafrost regions [1, 2]). Gas-hydrate resources are estimated as $(2800–25{,}000)\cdot 10^{12}$ m^3 [3, 4], and potential resources of methane in gas hydrates can reach $2\cdot 10^{16}$ m^3 [2–4]. A natural gas hydrate with a volume of 1 m^3 contains up to 180 m^3 of gas and 0.78 m^3 of water [3]. In seas and oceans, gas hydrates are encountered at a depth of 300–400 to 1000–1200 m and more [1, 3]. They saturate the upper layer of bottom sediments and occupy approximately 10–20% of the total volume of the latter [3, 4]. Gas-hydrate accumulations were found in many areas of the World Ocean and also on a significant portion of the bottom area of Lake Baikal [5]. The problem of well drilling in a gas-hydrate massif was considered in [6]. Extraction of gas from gas-hydrate massifs seems to be possible by means of their deliberate melting. In this case, warmer water from the subsurface layers can be used as a heat source. In the present paper, we consider the problem of gas washout from a gas hydrate with the use of circulation of warm water through the system of gas production. Figure 1 shows a possible technological scheme of the process of gas washout from a gas-hydrate massif, where the gas-production system consists of two coaxial cylindrical vertical channels (wells). The inner well is designed to transport the heat-carrying agent (warm water) to the open section of the well surrounded by the gas-hydrate massif (bottomhole). Moving upward over the bottomhole, which is a coaxial channel between the walls of the inner well and the massif surrounding the well, the heat-carrying agent washes the gas hydrate out. In this case, the gas and, in addition, water join the upward flow on the section $0 < z < z_{op}$ owing to gas-hydrate decomposition, and then this two-phase flow passes to the cased layer ($z_{op} < z < z_{cl}$).

Let us consider the regime of well operation with the pressure p_0^i and temperature T_0^i at the entrance of the inner well and also the pressure p_e at the exit of the outer well being maintained constant.

1. Constitutive Equations. Let the gas-hydrate massif have a constant temperature T_{h0} far from the well. As the temperature of water near the sea bottom is approximately 4°C, we assume in our calculations that $T_{h0} = 4$°C ($T_{h0} = 277$ K). Let $p_{h0} = p_s(T_{h0})$ be the equilibrium pressure corresponding to the initial temperature T_{h0} (at $T = T_{h0}$ and $p = p_{h0}$, the gas hydrate can be in the equilibrium state with its decomposition products, i.e., with water and gas). The equilibrium pressure for the methane gas hydrate at this temperature is $p_{h0} \approx 3$ MPa. Therefore, the depth h of the sea whose bottom can be covered by the gas-hydrate layer should satisfy the condition

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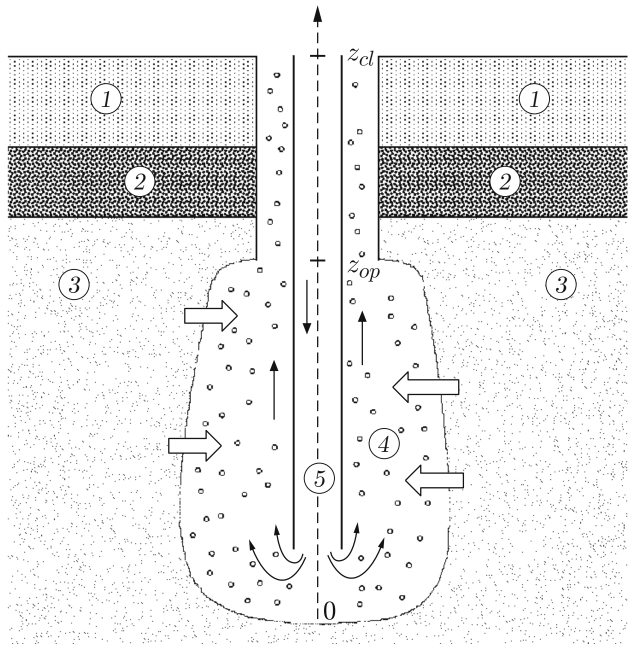

Fig. 1. Technological scheme of gas washout from a gas-hydrate massif: 1) water; 2) sediments; 3) gas-hydrate massif; 4) outer well; 5) inner well; the arrows indicate the directions of the heat-carrying agent and gas-hydrate flows.

$p_A + \rho_l^0 hg \geqslant p_{h0}$ (p_A is the atmospheric pressure, ρ_l^0 is the water density, and g is the free-fall acceleration). Thus, for the minimum depth $h_{\min}$, we obtain the condition $h_{\min} = (p_{h0} - p_A)/(\rho_l^0 g) \approx 300$ m.

The axial coordinate is counted from the lower boundary of the well bottomhole. The outer wall of the bottomhole is assumed to be an axisymmetric surface with the radius a depending on the vertical coordinate z and time t $[a = a(z,t)]$.

Under the assumption that the downward flow of the heat-carrying agent occurs with a constant velocity, the equation of momentum is written in the form

$$\frac{dp^i}{dz} = -\rho_l^0 g + \frac{2\tau_c^-}{a_c^-}, \tag{1.1}$$

where p^i is the pressure in the inner well, a_c^- is the radius of the inner well, and τ_c^- is the force of hydraulic friction between the flow and the wall per unit area of the latter. The equation of heat balance in the inner well has the form

$$m_l^- c_l \frac{dT^i}{dz} = 2\pi a_c^- q_c^- \qquad [m_l^i = \pi (a_c^-)^2 w^i \rho_l^0], \tag{1.2}$$

where T^i, m_l^i, w^i, and c_l are the temperature, mass flow, velocity, and specific heat of water, respectively, q_c^- is the heat-transfer intensity per unit area of the wall of the inner well.

The gas–liquid flow in the well is presented in the quasi-one-dimensional and quasi-steady approximation: the mass flow, temperature, and composition of the two-phase mixture are determined by the velocity, temperature, and volume concentration of the gas phase averaged over the well cross section. The assumption of quasi-steadiness means the following. The well radius in the bottom region is changed owing to gas-hydrate washout. For this reason, the temperature and hydrodynamic processes in the gas-production system are unsteady (despite constant conditions maintained at the entrance and exit). The characteristics time of the radius increase (e.g., a twofold increase) is substantially greater than the characteristic time of flow stabilization in cylindrical channels with constant conditions at the entrance and exit. As these characteristic times are determined by wave processes and also by the residence time of the gas–liquid system in the channel, the terms containing partial derivatives with respect to time in the mass, momentum, and energy equations can be neglected.

The equations of mass for the liquid and gas phases are written in the one-velocity approximation as

$$\frac{dm_i}{dz} = 2\pi a j_i, \qquad m_i = Sw\rho_i^0\alpha_i, \quad i \equiv g, l,$$
$$\alpha_g + \alpha_l = 1, \qquad S = \pi(a^2 - (a_c^+)^2). \tag{1.3}$$

Here m_i, ρ_i^0, and α_i are the mass flow, true density, and volume fraction of the ith phase (the subscripts g and l refer to the gas and liquid phases, respectively), w is the mean mass velocity, and j_i is the mass intensity of the income of the ith phase owing gas-hydrate washout from the well wall by warm water, per unit area of the wall. As the gas and water in the gas hydrate are in the stoichiometric ratio, we obtain

$$j_g = Gj, \qquad j_l = (1 - G)j, \tag{1.4}$$

where G is the mass concentration of the gas inside the gas hydrate and j is the mass intensity of gas-hydrate washout per unit area of the well surface.

Under the assumptions made, the equation of momentum can be written in the form [7, 8]

$$m\,\frac{dw}{dz} = -S\,\frac{dp}{dz} - S\rho g - 2\pi a\tau - 2\pi a_c^+\tau_c^+ - 2\pi a j w,$$
$$m = m_g + m_l, \qquad \rho = \rho_g^0\alpha_g + \rho_l^0\alpha_l, \tag{1.5}$$

where τ and τ_c^+ are the forces of friction between the gas–liquid flow and the outer wall of the well and between the gas–liquid flow and the outer wall of the inner channel per unit area. The last term in Eqs. (1.5) describes the reactive force induced by decomposition of the gas hydrate when the mixture enters the flow with a zero velocity with respect to this flow.

Similar to Eq. (1.5), the equation of heat income for the two-phase flow is presented as

$$(m_g c_g + m_l c_l)\,\frac{dT}{dz} = \frac{m_g}{\rho_g^0}\,\frac{dp}{dz} + 2\pi a j c(T_a - T) + 2\pi a q^- + 2\pi a_c q_c^+,$$
$$c = c_g G + c_l(1 - G). \tag{1.6}$$

Here T and T_a are the temperatures of the two-phase flow in the outer well and its wall, c_i ($i \equiv g, l$) are the specific heats of the gas and water (at constant pressure), q^- is the intensity of heat transfer between the two-phase flow in the outer well and its outer wall per unit area of this wall, and q_c^+ is the intensity of heat transfer between the two-phase flow in the outer well and the outer wall of the inner well per unit area of this wall. The second term in the right side of Eq. (1.6) describes the change in temperature on the open section of the well ($0 < z < z_{op}$) owing to flow dilution by the products of gas-hydrate decomposition. For the cased area of the well ($z_{op} < z < z_{cl}$), the terms due to the presence of phase transitions in Eqs. (1.3)–(1.6) are equal to zero ($j = 0$). The liquid is assumed to be incompressible, and the gas is assumed to be calorically perfect:

$$\rho_l^0 = \text{const}, \qquad p = \rho_g^0 R_g T. \tag{1.7}$$

2. Force and Thermal Interaction of the Flow in the Well with the Well Walls. The friction force and intensity of heat transfer between the heat-carrying agent and the inner surface of the well is taken into account by the Kirillov–Petukhov scheme [9], which implies that

$$\tau_c^- = \xi_c^-\rho_l^0(w^i)^2/8, \qquad \xi_c^- = (1.82\log \mathrm{Re}_l - 1.64)^{-2},$$
$$q_c^- = \beta_c^-(T^i - T_c^-), \qquad \beta_c^- = \lambda_l\,\mathrm{Nu}_l^-/(2a_c^-), \tag{2.1}$$
$$\mathrm{Nu}_l^- = \frac{(\xi_c^-/8)\,\mathrm{Re}_l\,\mathrm{Pr}_l}{1.07 + 12.7\sqrt{\xi_c^-/8}\,(\mathrm{Pr}_l^{2/3} - 1)}, \qquad \mathrm{Pr}_l = \frac{\mu_l c_l}{\lambda_l}, \qquad \mathrm{Re}_l = \frac{2a_c^-\rho_l w_l}{\mu_l},$$

where T_c^- is the temperature of the inner surface of the well.

For the force and thermal interaction of the upward flow with the walls, we use the relations

$$\tau_c^+ = \tau = \xi\rho w^2/8, \quad \xi = (1.82\log \mathrm{Re} - 1.64)^{-2}, \quad q_c^+ = \beta_c^+(T_c^+ - T), \quad q^- = \beta^-(T_a - T),$$

$$\beta_c^+ = \frac{\lambda\,\mathrm{Nu}}{2(a-a_c^+)}, \quad \beta^- = \frac{\lambda\,\mathrm{Nu}}{2(a-a_c^+)}, \quad \mathrm{Nu} = \frac{(\xi/8)\,\mathrm{Re}\,\mathrm{Pr}}{1.07 + 12.7\sqrt{\xi/8}\,(\mathrm{Pr}^{2/3}-1)}, \tag{2.2}$$

$$\mathrm{Re} = \frac{2(a-a_c^+)\rho w}{\mu}, \qquad \mathrm{Pr} = \frac{\mu c}{\lambda},$$

where T_c^+ and T_a are the temperatures of the outer wall of the inner well and the outer wall of the outer well).

In the expressions for q_c^- and q_c^+, the unknown temperatures T_c^- and T_c^+ can be eliminated. For the sake of generality, we take into account the thermal resistance of the walls of the inner well. Assuming that the thickness of the wall of the inner well is much smaller than its radius ($\Delta a \ll a_c^-$ and $\Delta a = a_c^+ - a_c^-$), the heat flux through the walls of the inner well can be determined from the relations

$$q_c = \beta_c(T_c^- - T_c^+), \qquad \beta_c = \lambda_c/\Delta a_c, \tag{2.3}$$

where λ_c is the thermal conductivity of the inner well material. As the heat fluxes q_c^-, q_c, and q_c^+ should be identical, we obtain

$$q_c^- = q_c = q_c^+ = \beta(T^i - T), \tag{2.4}$$

where

$$1/\beta = 1/\beta_c^- + 1/\beta_c + 1/\beta_c^+. \tag{2.5}$$

The dynamic viscosity μ and thermal conductivity λ for the gas–liquid mixture are found by the formulas

$$\mu = \mu_g\alpha_g + \mu_l\alpha_l, \qquad \lambda = \lambda_g\alpha_g + \lambda_l\alpha_l. \tag{2.6}$$

3. Description of Gas-Hydrate Washout Intensity. We assume that the local intensity j of gas-hydrate destruction (washout) on the well surface is limited by the intensity of heat addition to this surface. The temperature of the wall of the outer well T_a equals the equilibrium temperature of gas-hydrate decomposition T_s corresponding to the upward flow pressure p in this cross section, which is determined by the coordinate z [$T_a = T_s(p)$]. For the dependence $T_s(p)$, we use the expression [10]

$$T_s(p) = T_{h0} + T_*\ln(p/p_{h0}). \tag{3.1}$$

Based on the considerations described above, we obtain

$$j = \frac{q^- - q^+}{l_h}, \qquad q^+ = -\lambda_h\Big(\frac{\partial T_h}{\partial r}\Big)_a. \tag{3.2}$$

Here q^+ is the intensity of heat transfer from the well wall to the gas-hydrate massif and λ_h and l_h are the thermal conductivity and the specific heat of gas-hydrate decomposition, respectively. In the description of the temperature field in the gas-hydrate massif, we assume that the temperature gradients in the gas hydrate along the well are smaller than those in the radial direction ($|\partial T_h/\partial z| \ll |\partial T_h/\partial r|$); hence, the heat-conduction equation for the gas-hydrate temperature distribution near the well walls acquires the form

$$\rho_h^0 c_h\frac{\partial T_h}{\partial t} = \lambda_h r^{-1}\frac{\partial}{\partial r}\Big(r\frac{\partial T_h}{\partial r}\Big) \qquad (a < r < \infty). \tag{3.3}$$

The value of temperature should satisfy the following boundary conditions:

$$T_h = T_a \quad (r = a), \qquad T_h = T_{h0} \quad (r = \infty). \tag{3.4}$$

At the initial time (before the beginning of well operation), the temperature field should satisfy the condition

$$T_h = T_{h0} \qquad (t = 0, \quad r \geqslant a_0). \tag{3.5}$$

The rate of variation of the well radius $a = a(z,t)$ is found from the equation

$$\frac{\partial a}{\partial t} = \frac{j}{\rho_h^0}. \tag{3.6}$$

4. Approximate Description of Temperature Fields Near the Well. If the rate of temperature variation near the well is small, then the method based on the assumption about a finite radius of the thermal influence of the well $r = a_*$ is commonly used [11–13]. According to this method, the temperature field near the well is described by the expression

$$T_h = C_1 \ln(r/a) + C_2 r + C_3 \tag{4.1}$$

satisfying the following boundary conditions on the well wall and on the surface limiting the thermal influence of the well:

$$r = a\colon \quad T_h = T_a, \qquad r = a_*\colon \quad T_h = T_{h0}, \quad \frac{\partial T_h}{\partial r} = 0. \tag{4.2}$$

From conditions (4.2), we obtain the following relations for the coefficients C_1, C_2, and C_3:

$$C_2 = \frac{T_{h0} - T_a}{a_* - a - a_* \ln(a_*/a)}, \qquad C_1 = -a_* C_2, \qquad C_3 = T_a - aC_2. \tag{4.3}$$

The law of variation of the radius a_* is determined on the basis of the equation of heat balance in the gas-hydrate layer $a < r < a_*$ near the well:

$$\frac{\partial}{\partial t} \int\limits_a^{a_*} 2\pi r c_h \rho_h^0 (T_h - T_{h0})\, dr = -2\pi a \lambda_h \Big(\frac{\partial T_h}{\partial r}\Big)\Big|_{r=a}. \tag{4.4}$$

Substituting Eq. (4.1) into Eq. (4.4) and taking into account Eq. (4.3), we obtain the differential equation

$$\frac{\partial}{\partial t} \frac{6a_*^3 \ln(a_*/a) - 3a_*(a_*^2 - a^2) - 4(a_*^3 - a^3) + 6a(a_*^2 - a^2)}{a_* - a - a_* \ln(a_*/a)} = -12\nu_h \frac{a_* - a}{a_* - a - a_* \ln(a_*/a)}, \tag{4.5}$$

where $\nu_h = \lambda_h/(\rho_h^0 c_h)$.

In Eqs. (4.4) and (4.5), we use the partial derivatives with respect to time, because the quantities a and a_* are functions of z: $a(t, z)$ and $a_*(t, z)$. To determine the well radius, we obtain one more differential equation from Eq. (3.6) with allowance for Eqs. (3.1), (4.1), and (4.3):

$$\frac{\partial a}{\partial t} = \frac{q^- - q^+}{\rho_h^0 l_h}, \qquad q^+ = -\lambda_h \frac{(T_{h0} - T_a)(a - a_*)}{a(a_* - a - a_* \ln(a_*/a))}. \tag{4.6}$$

5. Boundary Conditions for Hydrodynamic and Thermal Fields in a System of Wells. We consider the well operation regime with the pressure at the entrance of the inner well p_0 and the pressure at the exit of the outer well (or at the well mouth) p_e being maintained constant, and the temperature of the heat-carrying agent at the entrance of the inner well is also assumed to be constant. At $z = z_{cl}$, these conditions can be written in the form

$$p^i = p_0, \qquad p = p_e, \qquad T^i = T_0. \tag{5.1}$$

Other regimes of well operation are also possible; for instance, we can use the conditions of a constant mass flow and temperature of the heat-carrying agent at the entrance of the inner well and also the condition of a constant pressure at the well mouth. These conditions should be supplemented by the condition of matching of the hydrodynamic fields (velocities and pressures) near the exit from the inner well ($z = 0$): 1) condition of mass balance for the liquid on this boundary; 2) conditions

$$\begin{gathered} m_l^i = m_l, \qquad \rho_l^0 (w^i)^2/2 + p^i = \rho_l^0 w^2/2 + p, \\ m_l^i = \pi (a_c^i)^2 w^i \rho_l^0, \qquad m_l = \pi(a^2 - (a_c^+)^2) w \rho_l^0, \end{gathered} \tag{5.2}$$

which occur near this boundary owing to expansion of the stream tube of the outflowing liquid and a significant increase in pressure (in the initial approximation, this can be taken into account with the Bernoulli integral). Conditions similar to (5.2) should also be imposed in the region of the transition of the upward flow from the open section to the cased section. In this case, the conditions of matching for such channels at $z = z_{op}$ acquire the following form:

$$\begin{gathered} m_{l(-)} = m_{l(+)}, \qquad m_{g(-)} = m_{g(+)}, \\ m_{l(\mp)} = \pi(a_{(\mp)}^2 - (a_c^+)^2) w_{(\mp)} (1 - \alpha_{g(\mp)}), \qquad m_{g(\mp)} = \pi(a_{(\mp)}^2 - (a_c^+)^2) w_{(\mp)} \alpha_{g(\mp)}. \end{gathered} \tag{5.3}$$

The pressures $p_{(-)}$ and $p_{(+)}$ can also be matched on the basis of the Bernoulli integral with allowance for mixture compressibility caused by the presence of the gas phase, with the help of the expression

$$\frac{w_{(+)}^2}{2} - \frac{w_{(-)}^2}{2} = -\int\limits_{p_{(-)}}^{p_{(+)}} \frac{dp}{\rho} \tag{5.4}$$

(ρ is the mean density of the gas–liquid mixture). Assuming that the gas–liquid mixture in the one-velocity and isothermal flows is compressible only if it contains the gas phase, we obtain the following equation of state [5]:

$$\frac{p}{p_{(-)}} = \frac{(\rho_{(-)} - \rho_l^0)\rho}{(\rho - \rho_l^0)\rho_{(-)}}. \tag{5.5}$$

With allowance for Eq. (5.5), Eqs. (5.3) and (5.4) with known values of $a_{(-)}$ and $a_{(+)}$, and also $w_{(-)}$, $\alpha_{g(-)}$, and $p_{(-)}$ allow us to determine the values of $w_{(+)}$, $\alpha_{g(+)}$, and $p_{(+)}$.

6. Transformation of Equations to a Form Convenient for Numerical Calculations. With allowance for condition (5.1), the equation for pressure (1.1) can be integrated:

$$p^i = p_0 + (\rho_l^0 g - 2\tau_c^-/a_c^-)(z_{cl} - z). \tag{6.1}$$

For a known value of the mass flow m_l^i (and, hence, w^i and τ_l^-), Eq. (6.1) allows us to find the pressure distribution along the inner well, in particular, the value of pressure at the bottom ($z = 0$).

Equations (1.2) are presented in the form

$$\frac{dT^i}{dz} = \frac{2q_c^-}{\rho_l^0 c_l w^i a_c^-}. \tag{6.2}$$

For the values of a and a_* "frozen" in time, relations (2.1)–(2.6) and (3.1)–(3.6) with allowance for Eq. (4.6) for q^+ form a closed system of ordinary differential equations. The quantities w, p, T, m_l, and m_g are assumed to be unknown functions. Eliminating the parameters α_g and α_l from Eqs. (1.3), we obtain the following relations for m_l and m_g:

$$m_l/\rho_l^0 + m_g/\rho_g^0 = Sw. \tag{6.3}$$

Differentiating Eq. (6.3) with allowance for the equations of state (1.7), we find

$$S\,\frac{dw}{dz} + \frac{m_g}{\rho_g^0 p}\,\frac{dp}{dz} - \frac{m_g}{\rho_g^0 T}\,\frac{dT}{dz} = f_m, \tag{6.4}$$

where

$$f_m = \frac{1}{\rho_l^0}\,\frac{dm_l}{dz} + \frac{1}{\rho_g^0}\,\frac{dm_g}{dz} - w\,\frac{dS}{dz}.$$

Transforming Eq. (6.4) with allowance for the equations of momentum (1.5) and heat income (1.6), we obtain

$$\frac{dw}{dz} = \frac{\Delta_w}{\Delta}, \qquad \frac{dp}{dz} = \frac{\Delta_p}{\Delta}, \qquad \frac{dT}{dz} = \frac{\Delta_T}{\Delta}, \tag{6.5}$$

where

$$\Delta = S^2(m_g c_g + m_l c_l) + \Big(\frac{m_g}{\rho_g^0}\Big)^2 \frac{m}{T} - (m_g c_g + m_l c_l)\,\frac{m_g}{\rho_g^0}\,\frac{m}{p},$$

$$\Delta_w = S(m_g c_g + m_l c_l) f_m + \Big(\frac{m_g}{\rho_g^0}\Big)^2 \frac{f_w}{T} + S\,\frac{m_g}{\rho_g^0}\,\frac{f_T}{T} - (m_g c_g + m_l c_l)\,\frac{m_g}{\rho_g^0}\,\frac{f_w}{p},$$

$$\Delta_p = S(m_g c_g + m_l c_l) f_w - m\,\frac{m_g}{\rho_g^0}\,\frac{f_T}{T} - m(m_g c_g + m_l c_l) f_m,$$

$$\Delta_T = S^2 f_T - m\,\frac{m_g}{\rho_g^0} f_m - m\,\frac{m_g}{\rho_g^0}\,\frac{f_T}{p} + S\,\frac{m_g}{\rho_g^0}\,f_w,$$

$$f_w = -S\rho g - 2\pi a\tau - 2\pi a_c^+\tau_c^+ - 2\pi a j w, \quad f_T = 2\pi a j c(T_a - T) + 2\pi a q^- + 2\pi a_c q_c^+.$$

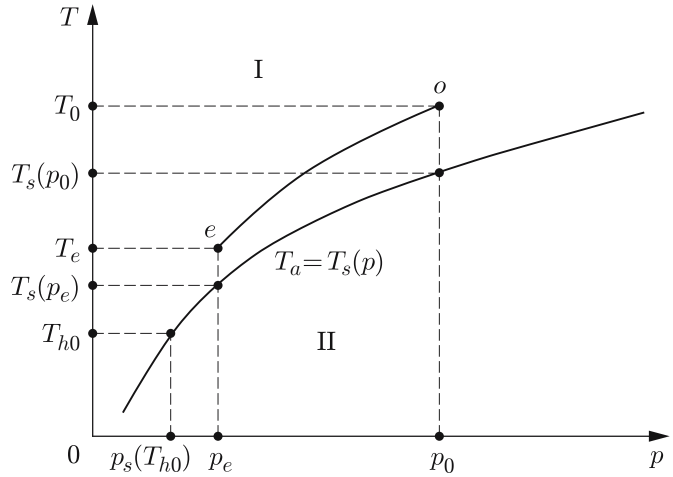

Fig. 2. Phase diagram: the regions containing the gas and water and containing the gas hydrate are indicated by I and II, respectively.

7. Calculation Results. Equations (6.5) allow us to perform numerical experiments on well operation in a gas-hydrate massif. The algorithm of calculating the time pattern of the processes considered includes two stages. At the first stage, with specified conditions at the entrance of the inner well and at the mouth of the outer well ($z = z_{cl}$),

$$p^i = p_0^i, \qquad T^i = T_0^i, \qquad p = p_e, \tag{7.1}$$

and with the distributions of a and a_* along the well being "frozen" in time, we solve the boundary-value problem and find the distributions of p^i, T^i, m_g, m_l, w, p, and T. At the second stage, on the basis of the distributions obtained at the first stage, we perform a time step: using Eqs. (4.5) and (4.6), we find the distributions of the radii a and a_* along the well for the text time instant. After that, we come back to the first stage.

Solving the Cauchy problem for Eqs. (6.1)–(6.5) with the "initial" conditions on the bottom ($z = 0$) being unknown in advance, we obtain the distribution of hydrodynamic parameters in the gas-production system. The unknown "initial" conditions are determined by means of adjustment with respect to two parameters, which can be the mass flow of the heat-carrying agent m_l^i and temperature T_0 at the bottom. Selection of these values is continued until the boundary conditions (7.1) for the temperature T^i and pressure p are satisfied with needed accuracy.

Figure 2 shows the phase diagram in the plane (p, T), which corresponds to the hydrodynamic and temperature situation in the well. For the gas hydrate to decompose on the well wall, the phase trajectory oe in this plane, which corresponds to the distribution of pressure and temperature of water in the well, should lie above the phase equilibrium curve. The segment of the phase equilibrium curve between the pressures p_e and p_0 corresponds to the gas-hydrate state (characterized by the dependence of temperature on the current pressure) on the well surface.

The solid curves in Figs. 3 and 4 are the profiles of the temperature and hydrodynamic fields along the well and the distributions of the bottomhole radius and gas-hydrate washout intensity at different time instants during well operation. The gas-production system consisting of two coaxial cylindrical vertical wells was assumed in the calculations to have the following parameters: length of the inner well $z = 400$ m, radius $a_c^- = 0.05$ m, length of the non-cased section of the outer well $z_{op} = 100$ m, well radius at the initial time ($t = 0$) $a = 0.1$ m, and constant radius of the cased section ($z_{op} < z < z_{cl}$) of the outer well $a = 0.1$ m. The following values were taken for the parameters determining the operation regime of the system of wells: $p_0^i = 6.23$ MPa, $p_e = 1$ MPa, and $T_0^i = 300$ K. The mass flow of the well is seen to decrease with time (see Fig. 3c), which is mainly caused by the reduction of the heat-transfer intensity owing to the decrease in the linear velocity of the upward two-phase flow in the bottomhole part of the well (see Fig. 3e), which, in turn, occurs because of the increase in the cross-sectional area of the well. Note, an increase in the bottomhole radius (Fig. 4b) leads to an increase in the well-surface area on which gas-hydrate washout occurs. Thus, the decrease in heat transfer owing to the decrease in the linear velocity of the flow is more significant than the increase in the area of the contact surface between the upward flow and the gas-hydrate massif. To maintain a high mass flow of the gas, therefore, it is necessary to take measures that enhance

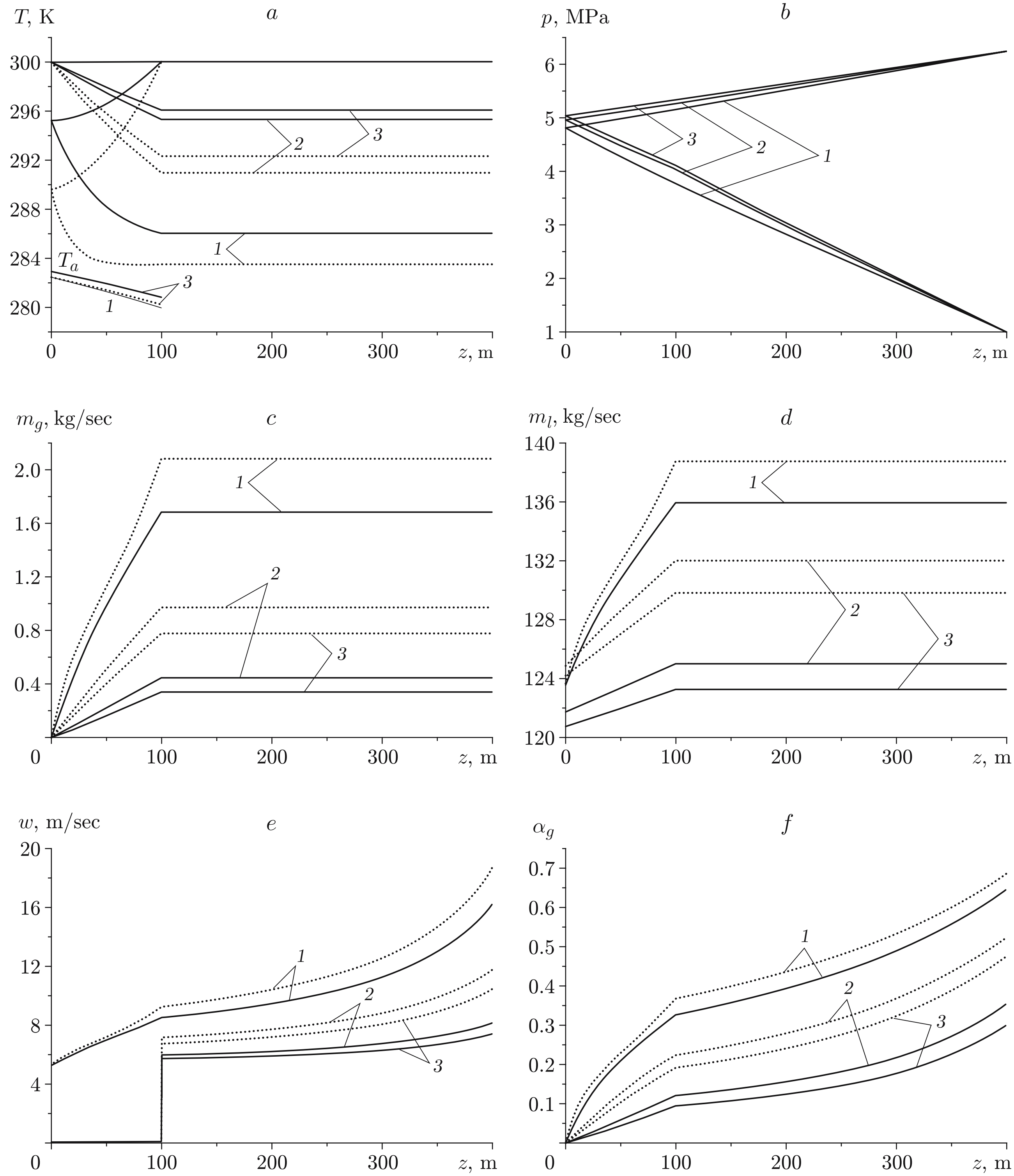

Fig. 3. Distributions of temperature (a) and hydrodynamic (b) fields, mass flows of the gas (c) and water (d), two-phase flow velocity (e), and volume concentration (f) along the well at different time instants: $t = 0$ (1), 5 h (2), and 10 h (3); the solid curves are calculated by the algorithm proposed in the present paper; the dotted curves are the results calculated with thrice increased current values of the heat-transfer coefficients β_c^+ and β^- in the outer well; the curves T_a are the distributions of the bottomhole wall temperature.

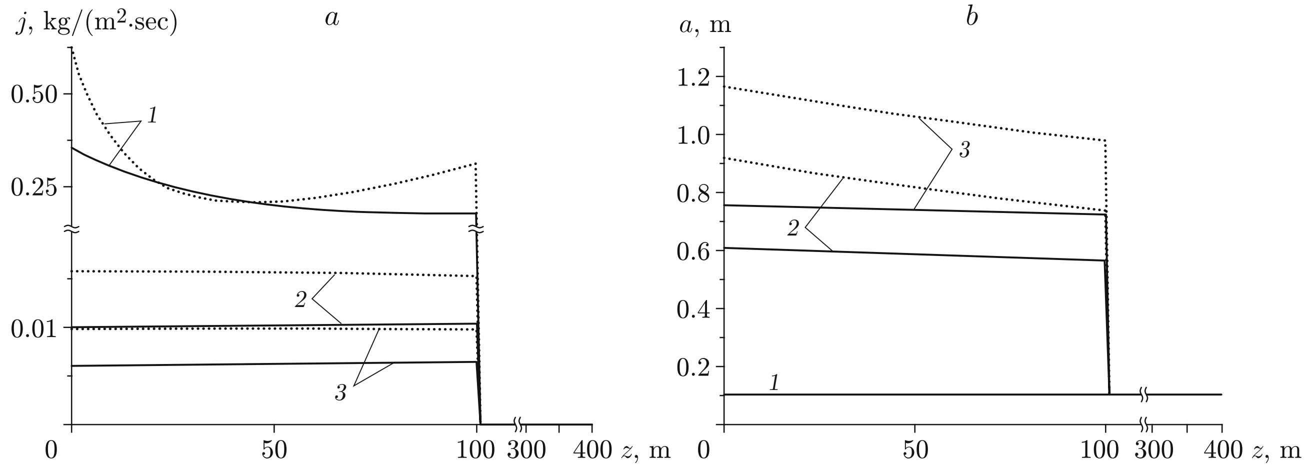

Fig. 4. Distributions of the gas-hydrate washout intensity (a) and bottomhole radius (b) at different time instants (notation the same as in Fig. 3).

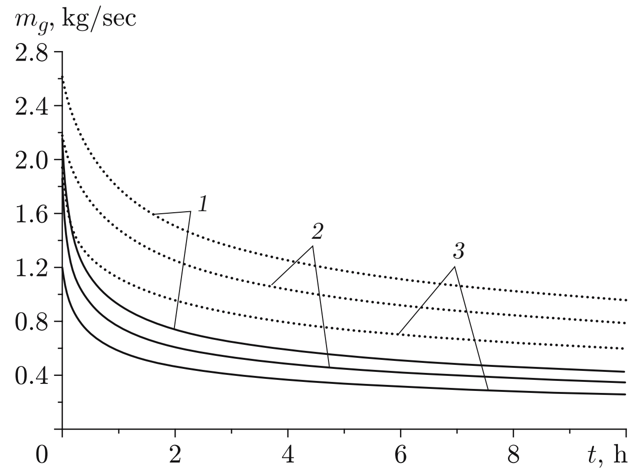

Fig. 5. Mass flow of the gas versus time for different initial temperatures of the heat-carrying agent: $T_0^i = 305$ (1), 300 (2), and 295 K (3); the remaining notations are the same as in Fig. 3.

the intensity of heat transfer from the upward flow to the bottomhole wall. (In Figs. 3–6, the effect of enhancement of the intensity of heat transfer from the upward flow to the walls of the gas-hydrate massif is illustrated by the dotted curves.) This can be reached by means of increasing the linear velocities near the walls (e.g., by means of flow swirling).

Figure 5 shows the mass flow of the gas escaping from the well as a function of time for three regimes of the gas-production system corresponding to different initial values of water temperature. The indicated values of temperature are used to calculate the pressure at the entrance of the inner well p_0^i and at the exit of the outer well p_e. It is seen that the mass flow of the gas increases with increasing temperature.

Figure 6 shows the effect of the well-mouth pressure on the mass flow of the gas. Regimes plotted in Fig. 6 are realized at constant values of the input pressure ($p_0^i = 6.23$ MPa) and temperature ($T_0^i = 300$ K) of the heat-carrying agent at the well entrance. It is seen that well operation with low well-mouth pressures is the most effective regime.

Figure 7 shows the effect of the length of the bottomhole section on the mass flow of the gas (the following values were taken for the parameters determining the regime of operation of the system of wells: $p_0^i = 6.23$ MPa, $p_e = 1$ MPa, and $T_0^i = 300$ K). Thus, the heat is more completely consumed in the system of wells with a larger length of the bottomhole; hence, such a system is more effective.

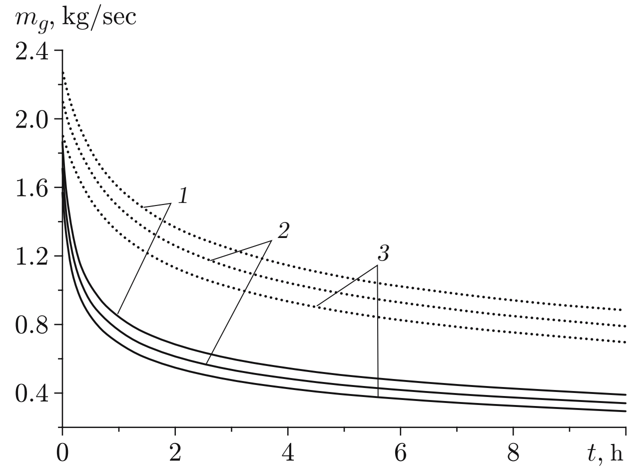

Fig. 6

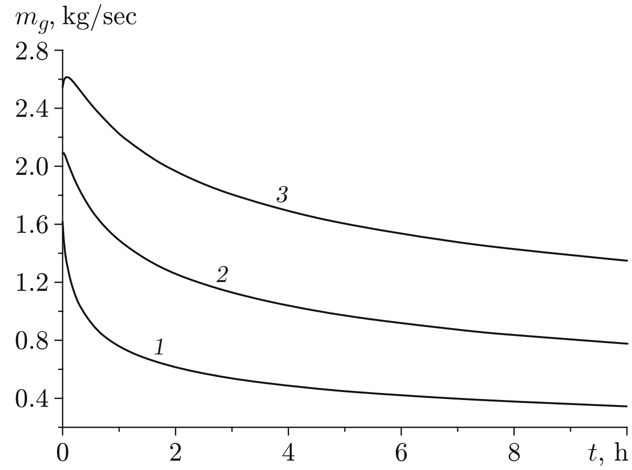

Fig. 7

Fig. 6. Mass flow of the gas versus time for different values of the well-mouth pressure: $p_e = 0.5$ (1), 1.0 (2), and 1.5 MPa (3); the remaining notations are the same as in Fig. 3.

Fig. 7. Mass flow of the gas versus time for different bottomhole lengths: $z_{op} = 100$ (1), 200 (2), and 300 m (3); the remaining notations are the same as in Fig. 3.

Conclusions. A technological scheme and a theoretical model of gas extraction from a gas-hydrate massif with the use of circulation of warm water in the gas hydrate are proposed. The possibility and expediency of this process are analyzed. Numerical experiments show that the efficiency of the proposed technological scheme can be improved by measures that ensure more complete consumption of heat brought by water to the bottomhole area. This can be reached by swirling the flow in the bottomhole, aimed at intensifying heat transfer, creating lower bottomhole pressures, and increasing the bottomhole section of the well.

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