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A FRONT PROBLEM CONCERNING THE DECOMPOSITION OF GAS HYDRATES IN NATURAL STRATA ON EXPOSURE TO HIGH-FREQUENCY ELECTROMAGNETIC RADIATION

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We consider a one-dimensional axial problem of gas filtration in front decomposition of gas hydrates in a porous medium on exposure to high-frequency electromagnetic radiation. Depending on the permeability of the medium, two basic regimes of the process are distinguished that differ in temperature distribution in the medium. The behavior of the hydrate decomposition front and of the pressure in this front depending on the absorption length of the medium is studied. The presence of an optimum regime for the most rapid decomposition of hydrate in a porous medium of prescribed dimensions is established.

According to the estimates made by specialists [1, 2], a considerable portion of the hydrocarbon raw material occurs naturally in the hydrate state: in strata (in the zones of frozen grounds) and in the coastal regions of seas (even in tropic zones). However, the extraction of gas from gas hydrate strata in a regular manner (heating by hot water or gas) is not sufficiently effective. At the same time, extraction of hydrate from a stratum by using high-frequency electromagnetic radiaton (HF EMR), similarly to the method of extraction of high-viscous oils, suggested in [3], seems to be promising.

I. We will consider a one-dimensional radial front problem concerning the decomposition of gas hydrate, which entirely fills a porous stratum in its initial state, and filtration of decomposition products on exposure to HF EMR, when phase transition occurs only on the surface of zero thickness. We will assume that in the zone of hydrate decomposition only the gas is filtered, whereas water is stagnant (which is the least advantageous regime for gas filtration). Then the system of equations in the zone of the decomposed hydrate takes the following form:

mass conservation equation for the gas

$$\frac{\partial}{\partial t}\,[m\overset{0}{\rho}_g S_g] + x^{-1}\,\frac{\partial}{\partial x}\,[xm\overset{0}{\rho}_g S_g v_g] = 0\,; \tag{1}$$

Darcy law for the filtering gas

$$mS_g v_g = -\frac{k_g}{\mu_g}\,\frac{\partial p}{\partial x}\,. \tag{2}$$

Equation of heat inflow for the system considered

$$\rho c\,\frac{\partial T}{\partial t} + m\overset{0}{\rho}_g S_g c_g v_g\,\frac{\partial T}{\partial x} = mS_g\left(\frac{\partial p}{\partial t} + v_g\,\frac{\partial p}{\partial x}\right) + x^{-1}\,\frac{\partial}{\partial x}\left(x\lambda\,\frac{\partial T}{\partial x}\right) + Q\,, \tag{3}$$

$$\rho c = (1 - m)\,\overset{0}{\rho}_r c_r + m\,(\overset{0}{\rho}_g S_g c_g + \overset{0}{\rho}_{\mathrm{liq}} S_{\mathrm{liq}} c_{\mathrm{liq}})\,,$$

$$\lambda = (1 - m)\,\lambda_r + m\,(S_g\lambda_g + S_{\mathrm{liq}}\lambda_{\mathrm{liq}})\,,$$

whereas in the zone where the hydrate has not yet been decomposed, the following equation of heat inflow holds:

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$$\rho c \frac{\partial T}{\partial t} = x^{-1} \frac{\partial}{\partial x} \left(x\lambda \frac{\partial T}{\partial x} \right) + Q . \tag{4}$$

A porous skeleton with the hydrate forms a perfect solid body; therefore, the distribution of pressure in this zone can be arbitrary with one condition for the stability of the hydrate: $p > p_s$ ($p_s = p_* \exp (T_0/T_*)$ is the equilibrium pressure at the temperature T_0.

The distribution of the heat sources Q, appearing due to the absorption of the HF EMR energy, will be determined according to [3] as

$$Q = \frac{N}{LF_e} \left(\frac{x_e}{x} \right) \exp \left(- \frac{x - x_e}{L} \right) , \tag{5}$$

where F_e is the area of the radiator surface; x_e is the position of the source boundary and the well radius.

The dependence of the absorption length L on the frequency and electrophysical properties of the material (the relative dielectric permeability ε and the tangent of dielectric losses $\tan \delta$) can be expressed as follows [3]:

$$L = C_0 \, (2\pi\omega \sqrt{\varepsilon} \tan \delta)^{-1} .$$

Generally speaking, for problems with a phase-transition surface on which electrophysical properties undergo a sudden change, one should account for the fact that electromagnetic waves (EMW) can reflect from this surface. Hereafter we will assume that reflection does not occur, since the electrophysical properties of the medium are largely determined by the properties of the porous skeleton, whose volumetric content is ~90%.

The boundary and initial conditions of the problem have the form

$$x = x_{(s)} : \overset{0}{\rho}_{g(s)} \, (v_g^- - \dot{x}_{(s)}) = - \overset{0}{\tilde{\rho}}_h \, \dot{x}_{(s)} ; \tag{6}$$

$$- \lambda^- \frac{\partial T^-}{\partial x} + \lambda^+ \frac{\partial T^+}{\partial x} = m \overset{0}{\rho}_h \, l \, \dot{x}_{(s)} ; \tag{7}$$

$$\begin{gathered} \overset{0+}{\rho}_g = \overset{0-}{\rho}_g = \overset{0}{\rho}_{g(s)} , \quad \overset{0}{\tilde{\rho}}_h = \overset{0}{\rho}_h g / S_g , \\ T_{(s)} = T_* \ln (p_{(s)}/p_*) ; \end{gathered} \tag{8}$$

$$x = x_e : \; p = p_e , \quad q_e = \left(\lambda \frac{\partial T}{\partial x} \right) = 0 ; \tag{9}$$

$$x = \infty : \; T = T_0 ; \tag{10}$$

$$t = 0 : \; T = T_0 . \tag{11}$$

We will reduce the system of equations to a dimensionless form. The following scales are used to make the quantities nondimensional:

$$T_0 , \; p_0 = p_* \exp (T_0/T_*) , \; L_0 , \; c_g , \; \overset{0}{\rho}_{g0} = p_0/RT_0 ,$$

$$v_0 = \frac{k_g p_0}{m S_g \mu_g L_0} , \quad t_* = L_0/v_0 .$$

Then we introduce the dimensionless variables and parameters:

$$
{}_i = \frac{\overset{0}{\rho}_i}{\overset{0}{\rho}_{g0}}, \quad \Theta = \frac{T}{T_0}, \quad P = \frac{p}{p_0}, \quad L_k^* = \frac{L_k}{L_0}, \quad C_i = \frac{c_i}{c_g},
$$

$$
= \frac{\lambda_1}{(\rho c)_1 \; v_0 L_0}, \quad \mathrm{Pe} = \frac{m S_g \overset{0}{\rho}_{g0} c_g v_0 L_0}{\lambda_1}, \quad \Gamma = \frac{(\gamma - 1)}{\gamma}, \tag{12}
$$

$$
\Lambda_i = \frac{\lambda_i}{\lambda_1}, \quad G_i = \frac{\lambda_i T_0}{m \overset{0}{\rho}_h \, i v_0 L_0}, \quad N_k^* = \frac{N}{v_0 L_k \, (\rho c)_k \, F_e T_0}, \quad \tau = \frac{t}{t_*},
$$

$$
{}^*_h = \frac{\overset{0}{\rho}_h g}{\overset{0}{\rho}_{g0} S_g}, \quad q^* = \frac{q_e L_0}{\lambda_0 F_e T_0}, \quad X = \frac{x}{L_0}, \quad X_e = \frac{x_e}{L_0}, \quad X_{(s)} = \frac{x_{(s)}}{L_0}.
$$

In the new variables, the system of differential equations (1)-(4) with allowance for Eqs. (11) and (12) is transformed to two parabolic-type nonlinear differential equations in the region of the decomposed hydrate $X_e < X < X_{(s)}$ and to one equation of a similar type in the region of the undecomposed hydrate $X > X_{(s)}$:

$$
X_e < X < X_{(s)}: \; \frac{\partial \;{}_g}{\partial \tau} = X^{-1} \frac{\partial}{\partial X} \left(X \;\; {}_g \frac{\partial P}{\partial X} \right); \tag{13}
$$

$$
\frac{\partial \Theta}{\partial \tau} - D \;\; {}_g \, \mathrm{Pe} \frac{\partial P}{\partial X} \frac{\partial \Theta}{\partial X} = D X^{-1} \frac{\partial}{\partial x} \left(\Lambda_1 X \frac{\partial \Theta}{\partial X} \right) +
$$

$$
+ \Gamma D \, \mathrm{Pe} \frac{\partial P}{\partial \tau} - \Gamma D \, \mathrm{Pe} \frac{\partial P}{\partial X} \frac{\partial P}{\partial X} + N_* \left(\frac{X_e}{X} \right) \exp \left(- \frac{X - X_e}{L_1^*} \right); \tag{14}
$$

$$
X > X_{(s)}: \; \frac{\partial \Theta}{\partial \tau} = D X^{-1} \frac{\partial}{\partial X} \left(\Lambda_2 X \frac{\partial \Theta}{\partial X} \right) + N_* \left(\frac{X_e}{X} \right) \exp \left(- \frac{X - X_e}{L_2^*} \right). \tag{15}
$$

The initial condition and the conditions prescribed on the mobile front of phase transformation and on the boundaries of the region investigated take the form

$$
X = X_{(s)}: \; - G_1 \frac{\partial \Theta}{\partial X} + G_2 \frac{\partial \Theta}{\partial X} = \dot{X}_{(s)}; \tag{16}
$$

$$
\frac{\partial P}{\partial X} = \left(\frac{{}^*_h}{{}_g} - 1 \right) \dot{X}_{(s)}; \tag{17}
$$

$$
X = X_e: \; P = P_e, \; q^* = 0; \tag{18}
$$

$$
X = X_\infty: \; \Theta = 1, \; \tau = 0: \; \Theta = 1. \tag{19}
$$

It is evident that the problem is determined by the following dimensionless numbers and combinations that correspondingly characterize:

- the geometrically spatial properties of the region investigated: m, X_c, X_∞;
- the thermal and electrophysical properties of the phases: $\mathfrak{R}_i$, C_i, L_i^*, D, Λ_i;

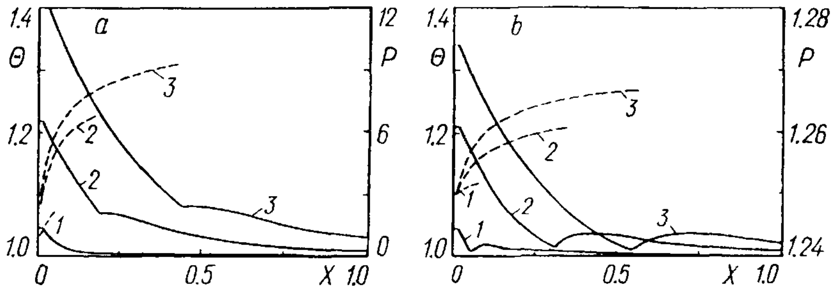


Fig. 1. Distribution of the dimensionless temperature and pressure at different time instants t = 10, 150, 350 days (curves 1, 2, 3) for low (a) and high (b) permeability of the porous medium ($k_{g0} = 10^{-17}$ and 10^{-13} m^2, respectively). The power of the HF EMR source is N = 10 kW/m.

- the relative influence of convective energy transfer as compared to energy transfer due to heat conduction: Pe;
- the relative contribution to the change in the medium energy of the processes of heat conduction and phase transition: G_i;
- and, finally, the influence of external (boundary) conditions (in particular, of the volumetric heat source): N_*, Θ_0, P_e.

The system of equations (13)-(15) with boundary conditions (16)-(19) was solved by the pivot method using the method of split steps for tracking the front of hydrate decomposition.

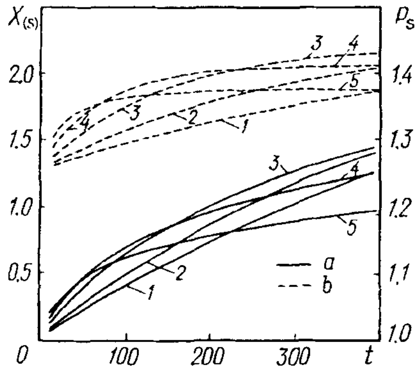
The above-mentioned method, suggested for solving the Stefan problem in a one-component substance, was developed in [3] to solve a problem of heat- and mass-transfer in a saturated porous medium with allowance for convective heat transfer and filtration of a weakly compressible fluid at a constant phase-change temperature. In the present work, the difference method with split steps of the front is generalized and applied for investigating filtration of a strongly compressed medium (gas), which is liberated on hydrate decomposition at the phase-transformation front, when the phase change temperature depends on the pressure behind the front.

All the calculations given below are carried out at the following values of the thermophysical and hydrodynamic parameters of the hydrate-porous medium system: $m = 0.1$; $T_0 = 283$ K; $p_0 = 5.08$ MPa; $T_* = 10$ K; $p^* = 2.6\cdot 10^{-6}$ Pa; $\rho_r^{\prime 0} = 2\cdot 10^3$ kg/m^3, $\rho_h^{\prime 0} = 0.9\cdot 10^3$ kg/m^3; $\rho_{\rm liq}^{\prime 0} = 10^3$ kg/m^3; $\mu_g = 1.8\cdot 10^{-5}$ Pa·sec; $\lambda_s = 2$ kg·m/sec^3·K; $\lambda_h = 2\cdot 11$ kg·m/sec^3·K; $\lambda_{\rm liq} = 0.58$ kg·m/sec^3·K; $\lambda_g = 3\cdot 10^{-2}$ kg·m/sec^3·K; $c_r = 1000$ J/kg·K; $c_h = 2500$ J/kg·K; $c_{\rm liq} = 4200$ J/kg·K; $l = 5\cdot 10^5$ J/kg; $L_0 = 25$ m; $g = 0.12$.

We note that at large powers of the high-frequency radiation source the temperature of the medium near the porous-medium boundary increases with time up to the values at which water (one of the products of hydrate decomposition) boils up, which substantially changes the picture of the process; the mathematical model used makes no provision for the boiling of liquid.

Calculations show that it is possible to distinguish two typical regimes of the decomposition of hydrate in a stratum on its exposure to high-frequency electromagnetic radiation. The first regime corresponds to small permeabilities of the porous stratum; it is characterized by a monotonic distribution of temperature over the entire volume and by a considerable increase in the temperature (and pressure) on the surface of phase transitions. The distributions of the temperature and pressure for such a regime at different time instants, t = 10, 150, and 350 days, are given in Fig. 1a. The dashed lines correspond to the case of the hydrate if it were not decomposed.

The second regime corresponds to large permeabilities of the stratum; it is characterized by the presence of a temperature "hole" ahead of the phase front and of the region of hydrate "overheating" behind the phase-transition front (by the temperature "hole" we mean the region where the temperature in the medium is lower than its values on the boundaries of the stratum; by "overheating" of the hydrate we mean the region behind the decomposition front, where the temperature is higher than its equilibrium magnitude, which corresponds to the pressure ahead of the front).



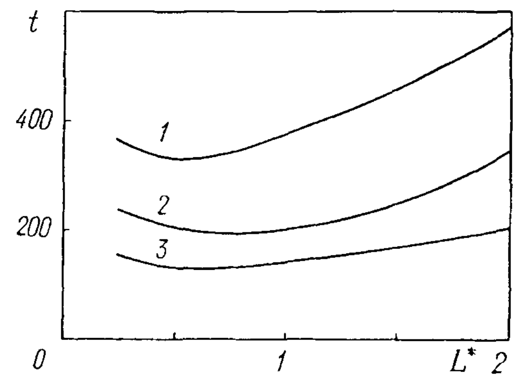


Fig. 2. Dependence of the coordinate of the decomposition front $X_{(s)}$ (a) (solid lines) and pressure at the front (b) on time for different values of the dimensionless absorption length $L^* = 0.25$, 0.5, 1, 2, 3. The power of the HF EMR source is $N = 40$ kW/m. t, days.

Fig. 3. Dependence of the time of melting through the 0.5-thick zone on the absorption length L^* for different values of the power of the HF EMR source: 1) $N = 10$ kW/m; 2) 20; 3) 30. t, days.

Figure 2 illustrates the evolution of the front of hydrate decomposition and of the pressure at this front for different values of the absorption length $L^* = 0.25$; 0.5; 1; 2; 3 (curves 1, 2, 3, 4, 5, respectively). An increase in the absorption length of the EMW energy by the medium L means an increase in the fraction of the EMA energy transmitted into the depth of the medium. This extends the time of hydrate decomposition and increases the time of front motion at the initial stage of heating and accelerates the front on subsequent heating. In the initial period of time, the front of phase transition X_s moves more rapidly in the case where L^* is smaller, but with an increase in time, the front conversely, will move more slowly for smaller absorption lengths. It turns out that the pressure (and accordingly the temperature) at the front of hydrate decomposition behaves nonmonotonically with time; it increases at the initial stage of heating, attains the maximum, and then decreases; moreover, the larger the absorption length, the later the pressure maximum is attained, and the larger the maximum pressure. Thus, for the preassigned dimensions of the zone X^* the minimum time for hydrate decomposition in this zone (and, consequently, the minimum energy expenditures) is attained for the absorption length $L^* \approx X^*$, just as for the heating of a porous medium saturated with solid bituminous oils [3]. The dependence of the time required for the hydrate decomposition front $X_{(s)}$ to penetrate into the medium and attain the depth $X^* = 0.5$, on the absorption length L^* (on radiation frequency) is presented in Fig. 3. We should note the following two formal limiting cases: the first case (when $L^* \Rightarrow 0$) indicates transition from volumetric heating of the medium with specific intensity Q to surface heating with power N; the second case (when $L^* \Rightarrow \infty$) is equivalent to the absence of a volumetric heat source ($Q = 0$). In this case, the finite radiated EMW energy is scattered uniformly in the space not heating the medium.

Thus, two regimes of hydrate decomposition in a stratum exposed to high-frequency electromagnetic radiation are established. In the case of low permeabilities, one should take into account the substantial (severalfold) increase in pressure near the hydrate decomposition front, whereas in the case of large permeabilities it is necessary to bear in mind the presence of a zone of temperature reduction near the hydrate decomposition front (possibly, below 0°C).

We show that by selecting the optimum radiation frequency (the absorption length of the medium) it is possible to realize the most rapid hydrate decomposition in the zone of prescribed dimensions (which is important, for example, in combating hydrate locks in the near-face zone of gas-producing wells), or the melting of hydrate in a certain time in the zone of the largest dimensions.

NOTATION

C_0, speed of light in a vacuum; c, specific heat, $m^2/(sec^2 \cdot K)$; k, absolute permeability coefficient, m^2; l, specific heat of phase transition, m^2/sec^2; L, length of absorption of electromagnetic waves by the medium, m; L^*, dimensionless absorption length; m, porosity; N, power of electromagnetic radiation source, kW/m; p, pressure, $kg/(m \cdot sec^2)$; P, dimensionless pressure; R, gas constant, $m^2/(sec^2 \cdot K)$; S_i, saturation; T, temperature, K; Θ, dimensionless temperature; t, time, sec; v, velocity, m/sec; Q, density of volumetric heat sources; x, coordinate, m; X, dimensionless coordinate; λ, thermal conductivity, $kg \cdot m/(sec^3 \cdot K)$; μ, dynamic viscosity, $kg/(m \cdot sec)$; ν, hydratosaturation; ρ, density, kg/m^3; $\mathfrak{R}$, dimensionless density; ω, electromagnetic radiation frequency, 1/sec; ε, relative dielectric permeability; g, mass content of a gas in hydrate; δ, loss factor; γ, specific heat ratio. Subscripts: 0, initial state; e, edge of a porous medium; (s), front of phase transition; s, parameters on the line of phase equilibrium (T, p); liq, liquid phase; g, gaseous phase; h, hydrate; r, porous skeleton; 1, zone of decomposed hydrate; 2; zone of undecomposed hydrate.

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