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THERMAL SHOCK UNDER THE ACTION OF RADIATION ENERGY ON A POROUS MEDIUM PARTIALLY FILLED WITH GAS HYDRATE

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Consideration has been given to the process of decomposition of a gas hydrate saturating a porous volume under the action of the energy of radiation through its boundary. It has been adopted that the zone lying in the vicinity of the boundary and saturated with the products of decomposition of the gas hydrate is transparent to radiation; the far zone saturated with gas hydrate and gas, conversely, is completely opaque; therefore, the radiation energy is totally absorbed at the boundary of phase transitions between the zones mentioned. The self-similar solutions of plane one-dimensional and radial-symmetric problems have been constructed. The influence of the radiation intensity and of the parameters of the porous medium–solid gas hydrate–gas system in the initial state on the maximum pressures produced in the zone of decomposition of the gas hydrate has been analyzed based on the analytical solutions obtained.

Formulation of the Problem and Basic Equations. Some problems of development of a thermal shock and associated possible ejections of gases in decomposition of gas hydrates in porous media have been considered in [1, 2]. By a thermal shock here we mean an increase in the pressure in the filtration zone because of the gas-hydrate decomposition involving intense heat release under the action of radiation energy or bulk heating. Let the radiator of energy (for example, of a high-frequency electromagnetic wave) be acting at the boundary of the region of a porous medium partially filled (in the initial state) with gas and partially with gas hydrate. We will assume that two zones are formed in the porous medium under such an action. The first zone, lying in the vicinity of the radiation source, contains only the products of decomposition of the hydrate (gas and water) in the pore channels, whereas a solid gas hydrate is absent. This zone is transparent to the process of radiation, which enables us to disregard the release of heat in the volume (we take this zone as an ideal dielectric in propagation of high-frequency electromagnetic waves). The gas hydrate and the gas are present in the porous channels in the second, far zone. We believe that, because of the presence of the gas hydrate, there is absorption of radiation in a thin layer, i.e., it is entirely carried out at the frontal boundary between the two zones where the total decomposition of the gas hydrate occurs [3]. The idealization taken above is based on the fact that most rocks, along with gas and distilled water, are good dielectrics, whereas high-frequency electromagnetic waves in gas hydrates propagate with a high loss. Let the volume fraction of the gas hydrate in the porous channels of the second zone be ν and be equal to the initial hydrate-saturation of the porous medium. In mathematical description of the processes of filtration and heat transfer, we have introduced the following assumptions: the skeleton, gas hydrate, and water are incompressible; the gas is calorifically perfect, the gas phase is mobile, and the water is immobile ($v_{\text{liq}} = 0$).

With allowance for the assumptions made, for one-dimensional problems we write the equations of conservation of mass, of heat inflow, and of state of the gas and Darcy's law [2]:

$$m_{(i)} \frac{\partial \rho_{g(i)}}{\partial t} + r^{-n} \frac{\partial}{\partial r} (r^n \rho_{g(i)} m_{(i)} v_{g(i)}) = 0 \,, \quad \rho_{(i)} c_{(i)} \frac{\partial T_{(i)}}{\partial t} + \rho_{g(i)} c_g m_{(i)} v_{g(i)} \frac{\partial T_{(i)}}{\partial r} =$$

$$= r^{-n} \frac{\partial}{\partial r} \left(\lambda_{(i)} r^n \frac{\partial T_{(i)}}{\partial r} \right) + m_{(i)} \left(\frac{\partial p_{(i)}}{\partial t} + v_{g(i)} \frac{\partial p_{(i)}}{\partial r} \right),$$

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$$u_{g(i)} = m_{(i)} v_{g(i)} = -\frac{k_{(i)}}{\mu_{g(i)}} \frac{\partial p_{(i)}}{\partial r} , \quad p_{(i)} = \rho_{g(i)} R_g T_{(i)} ,$$

$$m_{(1)} = m S_{g(1)} , \quad m_{(2)} = m (1 - \nu) , \tag{1}$$

$$\rho_{(1)} = (1 - m) \rho_{sk} + m S_{liq(1)} \rho_{liq} + m S_{g(1)} \rho_{g(1)} ,$$

$$\rho_{(2)} = (1 - m) \rho_{sk} + m \nu \rho_h + m (1 - \nu) \rho^0_{g(2)} , \quad S_{g(i)} + S_{liq(i)} = 1 .$$

The equations of balance of mass for the water and the gas and of heat at the boundary between the zones $r = r_{(s)}$ yield

$$m \nu \rho_h (1 - g) \dot{r}_{(s)} = m S_{liq(1)} \rho_{liq} \dot{r}_{(s)} ,$$

$$m \left[(1 - \nu) \rho_{g(s)} (v_{g(2)} - \dot{r}_{(s)}) - \nu \rho_h g \dot{r}_{(s)} \right] = m S_{g(1)} \rho_{g(s)} (v_{g(1)} - \dot{r}_{(s)}) , \tag{2}$$

$$\lambda_{(2)} \frac{\partial T_{(2)}}{\partial r} - \lambda_{(1)} \frac{\partial T_{(1)}}{\partial r} = m \nu \rho_h l \dot{r}_{(s)} - q .$$

At the boundary between the zones, the conditions of continuity of the pressure, the temperature, and hence the density of the gas are satisfied:

$$p_{(1)} = p_{(2)} = p_{(s)} , \quad T_{(1)} = T_{(2)} = T_{(s)} , \quad \rho_{g(1)} = \rho_{g(2)} = \rho_{g(s)} , \quad r = r_{(s)} . \tag{3}$$

Based on the first and second equations from (2) with account for Darcy's law from (1), we obtain

$$-\frac{k_{(2)}}{\mu_{g(2)}} \frac{\partial p_{(2)}}{\partial r} + \frac{k_{(1)}}{\mu_{g(1)}} \frac{\partial p_{(1)}}{\partial r} = m \nu \left[\frac{\rho_h g}{\rho_{g(s)}} + \frac{\rho_h (1 - g)}{\rho^0_{liq}} - 1 \right] \dot{r}_{(s)} , \quad r = r_{(s)} ,$$

$$S_{g(1)} = 1 - S_{liq(1)} = 1 - \nu \rho_h (1 - g) / \rho_{liq} . \tag{4}$$

For the values of temperature and pressure at the boundary between the zones the condition of phase equilibrium

$$T_{(s)} = T_0 + T_* \ln (p_{(s)} / p_{(s)0}) . \tag{5}$$

is satisfied.

The radiation source begins to act at the instant of time $t = 0$. In the case of the plane one-dimensional problem we will assume that the intensity of radiation absorption is constant (q = const), and for the radial problem we take

$$q = \frac{Q}{2 \pi r_{(s)}} . \tag{6}$$

Let us assume that at the initial instant of time the pressure p_0 and the temperature T_0 in the porous medium partially filled with gas hydrate are homogeneous with $p_0 \geq p_{(s)0}$:

$$p_{(2)} = p_0 , \quad T_{(2)} = T_0 , \quad t = 0 , \quad r \geq 0 . \tag{7}$$

For the plane one-dimensional problem ($n = 0$) we will assume that there is no heat flux at the boundary of the porous medium and the gas pressure varies by a certain law with time. These boundary conditions will be written as follows:

$$\lambda_{(1)} \frac{\partial T}{\partial r} = 0 \,, \quad p_{(1)} = p_{\mathrm{e}}^{0}(t) \,, \quad r = 0 \,, \quad t > 0 \,. \tag{8}$$

In the case of the radial problem we will assume that the heat flux is absent and extraction (or injection) of the gas with a constant intensity Q_{c} begins at the instant of time $t = 0$. These conditions will be represented in the form

$$2\pi r_{\mathrm{e}} \lambda_{(1)} \left(\frac{\partial T_{(1)}}{\partial r} \right)_{r_{\mathrm{e}}} = 0 \,, \quad 2\pi r_{\mathrm{e}} \frac{k_{(1)}}{\mu_{\mathrm{g}(1)}} \left(\rho_{\mathrm{g}(1)} \frac{\partial p_{(1)}}{\partial r} \right)_{r_{\mathrm{e}}} = Q_{\mathrm{c}} \,, \quad t > 0 \,, \quad r_{\mathrm{e}} \to 0 \,. \tag{9}$$

The evaluations show that in most cases of practical interest we can disregard the terms related to the convective transfer of heat and to the barothermal effect in the equation of heat inflow. Furthermore, in the piezoconductivity equation following from the equation of conservation of mass and Darcy's law, the term allowing for the variability of the temperature is small if the characteristic temperature differences ΔT in the filtration region are small (for example, when $\Delta T << T_0$). In what follows, we will also disregard the variability of the heat capacity per unit volume and of the thermal conductivity of the entire porous medium–gas hydrate–decomposition product system:

$$\rho_{(1)} c_{(1)} = \rho_{(2)} c_{(2)} = \rho c \,, \quad \lambda_{(1)} = \lambda_{(2)} = \lambda \,.$$

Then system (1) can be reduced to the form

$$\frac{\partial p_{(i)}}{\partial t} = r^{-n} \frac{\partial}{\partial r} \left(r^{n} \aleph^{(p)} \frac{\partial p_{(i)}}{\partial r} \right), \quad \frac{\partial T_{(i)}}{\partial t} = \aleph^{(T)} r^{-n} \frac{\partial}{\partial r} \left(r^{n} \frac{\partial T_{(i)}}{\partial r} \right),$$
$$\aleph^{(p)} = \frac{k_{(i)}}{\mu_{\mathrm{g}(i)} m_{(i)}} p_{(i)} \,, \quad \aleph^{(T)} = \frac{\lambda}{\rho c} \,. \tag{10}$$

Plane One-Dimensional Problem ($n = 0$). We will seek the solution in the form of a traveling wave when the boundary of phase transitions moves with a constant velocity

$$\dot{r}_{(\mathrm{s})} = v = \mathrm{const} \,.$$

We introduce a new variable $\xi = r - vt$. Integrating the first equation from (10), for the pressure in the second zone we obtain

$$v p_{(2)} + \frac{k_{(2)}}{\mu_{\mathrm{g}(2)} m_{(2)}} p_{(2)} \frac{d p_{(2)}}{d\xi} = C_{1(p)} \,. \tag{11}$$

From (7) it follows that we have $p_{(2)} \to p_0$ for $\xi \to \infty$; then the value of the constant can be written as $C_{1(p)} = v p_0$.

Having integrated Eq. (11) once again and having employed the equation of continuity of the pressure at the boundary of phase transitions ($\xi = \xi_{(\mathrm{s})} = 0$, $\Rightarrow p_{(2)} = p_{(\mathrm{s})}$), we obtain

$$p_0 \ln \left(\frac{p_{(2)} - p_0}{p_{(\mathrm{s})} - p_0} \right) - (p_{(\mathrm{s})} - p_{(2)}) = -\frac{v \mu_{\mathrm{g}(2)} m \,(1 - \nu_0)}{k_{(2)}} \xi \,, \quad \xi > 0 \,. \tag{12}$$

Analogously, the solution of Eq. (10), satisfying the condition $p_{(1)} = p_{(\mathrm{s})}$ for $\xi = 0$, will be written for the first zone in the form

$$p_{\mathrm{e}} \ln \left(\frac{p_{(1)} - p_{\mathrm{e}}}{p_{(\mathrm{s})} - p_{\mathrm{e}}} \right) - (p_{(\mathrm{s})} - p_{(1)}) = -\frac{v \mu_{\mathrm{g}(1)} m \,(1 - \nu_0)}{k_{(1)}} \xi \,, \quad \xi < 0 \,. \tag{13}$$

From condition (8), with account for (3), we consider the temperature in the first zone to be constant and equal to the temperature at the boundary $T_{(s)}$.

For the temperature distribution in the second zone the solution of the second equation from (10) will have the form

$$T_{(2)} = T_0 + (T_{(s)} - T_0)\exp\left(-\frac{v}{\aleph^{(T)}}\xi\right). \tag{14}$$

As follows from (13), the solution for the pressure distribution as a function of the coordinate ξ has an implicit form. If we carry out linearization (disregarding the variability of the piezoconductivity coefficient $\aleph^{(p)}$) in the piezoconductivity equation from (10), for the second zone we can write it in the form

$$\frac{d^2 p_{(2)}}{d\xi^2} + \frac{v}{\tilde{\aleph}^{(p)}}\frac{dp_{(2)}}{d\xi} = 0\,, \quad \tilde{\aleph}^{(p)} = \frac{k_{(2)}\tilde{p}}{\mu_{g(2)}m_{(2)}}\,, \tag{15}$$

where $\tilde{p}$ is a certain characteristic value of the pressure. The solution of this equation with account for initial (7) and boundary (8) conditions will be represented as

$$p_{(2)} = p_0 + (p_{(s)} - p_0)\exp\left(-\frac{v}{\tilde{\aleph}^{(p)}}\xi\right), \quad \xi > 0\,. \tag{16}$$

Analogously we can write the solution for the pressure distribution in the first zone:

$$p_{(1)} = p_e + (p_{(s)} - p_e)\exp\left(-\frac{v}{\tilde{\aleph}^{(p)}}\xi\right), \quad \xi < 0\,. \tag{17}$$

Apart from (16) and (17), we can obtain the solution by the Leibenzon linearization method [4]:

$$p_{(2)}^2 = p_0^2 + (p_{(s)}^2 - p_0^2)\exp\left(-\frac{v}{\tilde{\aleph}^{(p)}}\xi\right), \quad \xi > 0\,; \quad p_{(1)}^2 = p_e^2 + (p_{(s)}^2 - p_e^2)\exp\left(-\frac{v}{\tilde{\aleph}^{(p)}}\xi\right), \quad \xi < 0\,. \tag{18}$$

For solutions (13), (17), and (18) in the zone $0 < r < r_{(s)}$ (or $-vt < \xi < 0$) to satisfy the condition of absence of the gas hydrate ($p_{(1)} \le p_{(s)}$), the constant parameters $p_{(s)}$ and p_e must satisfy the condition $p_e \le p_{(s)}$. Furthermore, the pressure p_e^0 at the boundary ($r = 0$ or $\xi = -vt$) must be represented in the form

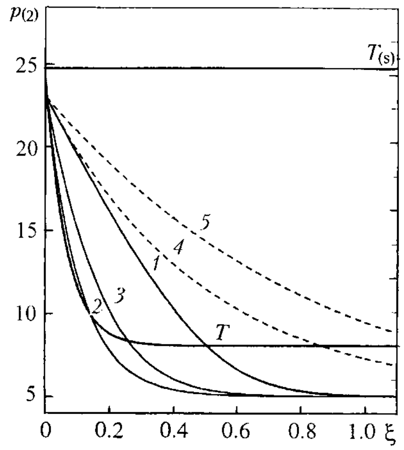
$$p_e^0 = p_e + (p_{(s)} - p_e)\exp\left(-\frac{v^2 t}{\aleph_{(1)}^{(p)}}\right). \tag{19}$$

The solution has a physical meaning ($p_{(1)} \ge 0$) during the time interval

$$0 \le t \le t_*\,, \quad t_* = \frac{\aleph_{(1)}^{(p)}}{v^2}\ln\left(\frac{p_e}{p_e - p_{(s)}}\right). \tag{20}$$

If we take $p_e = p_{(s)}$ in (13), (17), and (18), we obtain the solution $p_{(1)} = p_{(s)}$ corresponding to the condition of absence of extraction of the gas through the boundary $r = 0$ for the pressure distribution in the first zone ($0 < r < r_{(s)}$) (radiation energy is introduced through an impermeable boundary). Thus, when the energy is supplied through an impermeable boundary, in the porous medium there is formed an unusual kind of stationary shock wave with an amplitude $\Delta p = p_{(s)} - p_0$, which propagates with a constant velocity v, and the solutions (12) and (14) determine the structure of the leading edge.

In this case, on the basis of boundary conditions (2) and (4) and the solutions (12), we obtain an expression for determination of the velocity v of the phase-transition boundary and the parameters $p_{(s)}$ and $T_{(s)}$:



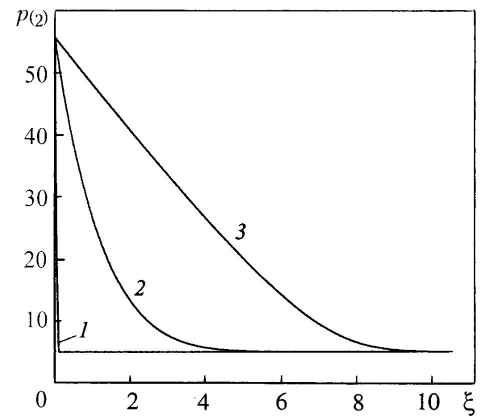


Fig. 1. Structure of the filtration zone in front of the boundary of phase transitions in the case where the boundaries of the porous medium are impermeable: 1) solution (12) (nonlinear case); 2) solution (16) ($\tilde{p} = p_0$); 3) solution (18) ($\tilde{p} = p_0$); 4 and 5) solutions (16) and (18) ($\tilde{p} = p_{(s)}$).

Fig. 2. Pressure in the second zone vs. self-similar coordinate ξ for different permeability factors: 1) $k_{(2)} = 10^{-19}$; 2) 10^{-18}; 3) 10^{-17} m^2.

$$v = \frac{q}{m\rho_h \nu l + \rho c\,(T_{(s)} - T_0)}\,, \quad (1-\nu)\,\frac{(p_{(s)} - p_0)}{p_{(s)}} = \nu\left(\frac{\rho_h g}{\rho_{g(s)}} + \frac{\rho_h\,(1-g)}{\rho_{liq}} - 1\right),$$
$$S_{g(1)} = 1 - \frac{\nu_0 \rho_h^0\,(1-g)}{\rho_{liq}^0}\,. \tag{21}$$

From the expressions obtained it is obvious that the pressure $p_{(s)}$ at the decomposition boundary is related to the initial hydrate-saturation of the bed and the initial bed pressure p_0 and is independent of the radiation-source strength; therefore, it is the intrinsic parameter of the initial hydrate-saturation of the porous medium. The maximum pressure is $p_{(s)} \approx 85$ MPa and it manifests itself when $\nu = 1$. The strength of the radiation source exerts an influence just on the velocity of motion of the phase-transition boundary and on the pressure and temperature profiles in the second zone.

Figure 1 gives the structure of the filtration zone in front of the boundary of phase transitions in the case where the boundaries of the porous medium are impermeable ($p_e = p_{(s)}$). For the parameters determining the initial state of the porous medium–solid gas hydrate–gas system we have taken the following values: $m = 0.1$, $\nu = 0.6$, $k_{(2)} = 10^{-18}$ m^2, $\mu_g = 10^{-5}$ Pa·sec, $\lambda = 2$ kg·m/(sec^3·K), $l = 5 \cdot 10^5$ J/kg, $R_g = 520$ J/(kg·K), $g = 0.12$, $\rho c = 2.5 \cdot 10^6$ J/(K·m^3), $T_0 = 275$ K, $p_0 = 5$ MPa, $q = 10^4$ W/m^2, and $v = 10^{-4}$ m/sec. Curves 1–5 correspond to the solutions (12), (16), and (18) and have been obtained under the assumption that $\tilde{p} = p_0$ and $\tilde{p} = p_{(s)}$. For the pressure and temperature in the first zone (in this case $p_{(1)} = p_{(s)}$ and $T_{(1)} = T_{(s)}$) we have $p_{(1)} = 23$ MPa and $T_{(1)} = 298$ K.

Figure 2 gives the pressure profiles in the second zone for different permeability factors $k_{(2)}$. It is seen that the width of the filtration zone is narrowed with decrease in the permeability factor.

We note that the solution (12) for $p_e = p_{(s)}$ also corresponds to the situation where one can disregard the influence of the hydraulic resistance of the medium's bed on the filtration of the gas ($k_{(1)} \to \infty$) in the zone of decomposition of the gas hydrate and a constant pressure $p_e^0 = p_{(s)}$ is maintained at the boundary of the porous medium. For the rate of filtration of the gas ($v_{g(1)} = \text{const}$ and $u_{g(1)} = m_{(1)} v_{g(1)}$) through the porous-medium boundary, based on (2) with account for (12), we can obtain

$$v_{g(1)} = mv\left(\frac{\rho_h g}{\rho_{g(s)}} + \frac{\rho_h\,(1-g)}{\rho_{liq}} - 1 - \frac{p_{(s)} - p_0}{p_{(s)}}\,(1-\nu)\right).$$

Here we note that, depending on the value of the pressure $p_{(s)}$, one can have the regime with gas extraction ($v_{g(1)} < 0$) or the regime with injection ($v_{g(1)} > 0$).

Radial Problem. In this case, the solution of system (10) with account for initial (7) and boundary conditions (9) has the form

$$T_{(1)} = T_{(s)}\,, \quad p_{(1)}^2 = p_0^2 + \frac{p_{(s)} Q_{(c)}\, \mu_{g(1)}}{\pi k_{(1)} \rho_{g(s)}} \int\limits_{\xi}^{\xi_{(s)}} \xi^{-1} \exp\left(-\frac{\xi^2}{4\eta_{(1)}}\right) d\xi\,, \quad 0 < \xi < \xi_{(s)}\,;$$

$$T_{(2)} = T_0 + (T_{(s)} - T_0) \frac{\int\limits_{\xi}^{\infty} \xi^{-1} \exp\left(-\frac{\xi^2}{4}\right) d\xi}{\int\limits_{\xi_{(s)}}^{\infty} \xi^{-1} \exp\left(-\frac{\xi^2}{4}\right) d\xi}\,;$$

$$p_{(2)}^2 = p_0^2 + (p_{(s)}^2 - p_0^2) \frac{\int\limits_{\xi}^{\infty} \xi^{-1} \exp\left(-\frac{\xi^2}{4\eta_{(2)}}\right) d\xi}{\int\limits_{\xi_{(s)}}^{\infty} \xi^{-1} \exp\left(-\frac{\xi^2}{4\eta_{(2)}}\right) d\xi}\,, \quad \xi_{(s)} < \xi < \infty\,; \tag{22}$$

$$\xi = \frac{r}{\sqrt{\aleph^{(T)} t}}\,, \quad \aleph^{(T)} = \frac{\lambda}{\rho c}\,, \quad \aleph_{(i)}^{(p)} = \frac{p_{(s)} k_{(i)}}{m_{(i)}\, \mu_{g(i)}}\,, \quad \eta_{(i)} = \frac{\aleph_{(i)}^{(p)}}{\aleph^{(T)}}\,.$$

We note that the solutions for the distribution of the pressure $p_{(i)}$ have been obtained by the Leibenzon linearization method. From the form of the solutions (22) for $p_{(s)}$ it follows that, when extraction of the gas is absent ($Q_c = 0$), an unusual kind of radial shock wave is also formed. However, the nature and structure of this pressure wave are quite different from the nature of a gasdynamic shock wave in gas dynamics. But, unlike the plane one-dimensional problem, its velocity is variable.

On the basis of conditions (2) and (4) at the boundary between the zones and with account for (6) we obtain the equation for the pressure $p_{(s)}$ and the self-similar coordinate of the phase-transition boundary $\xi_{(s)}$:

$$\eta_{(2)} m\, (1 - \nu) \frac{p_{(s)}^2 - p_0^2}{p_{(s)}^2} \frac{\exp\left(-\frac{\xi_{(s)}^2}{4\eta_{(2)}}\right)}{\int\limits_{\xi_{(s)}}^{\infty} \xi^{-1} \exp\left(-\frac{\xi^2}{4\eta_{(2)}}\right) d\xi} - \frac{Q_{(c)}}{\pi \aleph^{(T)} \rho_{g(s)}} \exp\left(-\frac{\xi_{(s)}^2}{4\eta_{(1)}}\right) = m\nu \left[\frac{\rho_h^0 g}{\rho_{g(s)}^0} + \frac{\rho_h^0 (1 - g)}{\rho_{liq}^0} - 1\right] \xi_{(s)}^2\,,$$

$$\frac{Q}{2\pi\lambda} - \frac{(T_{(s)} - T_0) \exp\left(-\frac{\xi_{(s)}^2}{4}\right)}{\int\limits_{\xi_{(s)}}^{\infty} \xi^{-1} \exp\left(-\frac{\xi^2}{4}\right) d\xi} = \frac{\mu\nu}{2} \frac{\rho_h^0 l}{\rho c} \xi_{(s)}^2\,. \tag{23}$$

For the law of motion of the phase-transition boundary we will have $r_{(s)} = \xi_{(s)} \sqrt{\aleph^{(T)} t}$.

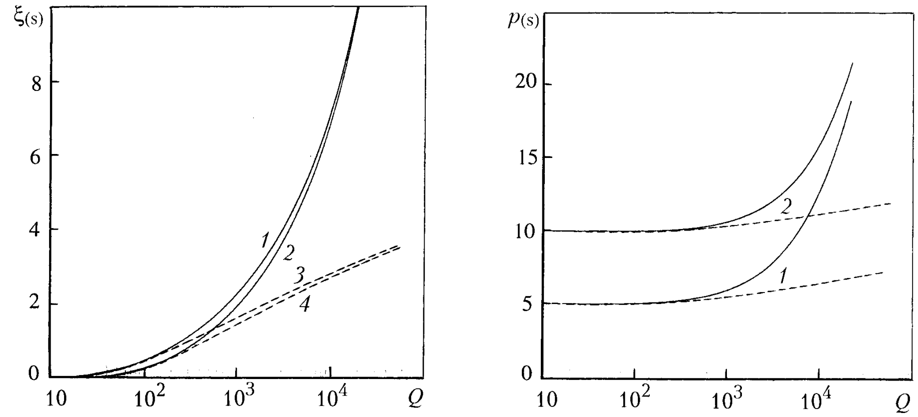


Fig. 3. Coordinate of the boundary $\xi_{(s)}$ and pressure at the boundary $p_{(s)}$ vs. source strength Q.

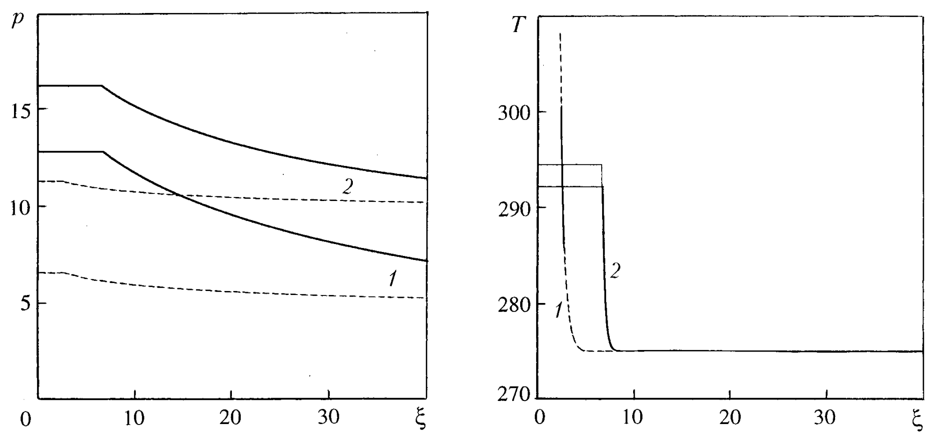


Fig. 4. Pressure and temperature profiles in the case of a thermal source and a superhigh-frequency-radiation source.

Figures 3 and 4 give some results of numerical calculations for the case $Q_c = 0$ (extraction or pumping of the gas are absent). Figure 3 gives (solid curves) the dependences of the self-similar coordinate of the phase-transition boundary $\xi_{(s)}$ and of the pressure $p_{(s)}$ on the source strength Q for values of the initial pressure of $p_0 = 5$ and 10 MPa (curves 1 and 2). The dashed curves 3 and 4 correspond to the solutions from [2], where heating is carried out by heat supply through the boundary of the porous medium by conduction. From the plots for $\xi_{(s)}$ is follows that, although the curves (solid and dashed) are similar for low values of Q ($Q \leq 10^3$ W/m), they differ strongly with increase in the strength. In particular, when $Q \approx 10^4$ W/m, the difference between them is ~2 times. The reason is that most of the energy supplied in thermal heating is expended in superheating the system in the first zone. In the case of the supply of energy by radiation it is mainly expended in decomposing the gas hydrate at the boundary of phase transitions.

Figure 4 illustrates the pressure and temperature profiles in the zones for the case of a thermal source and a superhigh-frequency-radiation source. In Fig. 4 on the right, curves 1 (dashed) correspond to the temperature profiles in the case of the thermal source at initial bed pressures of $p_0 = 5$ and 10 MPa. The difference between the profiles is quite small so that these curves virtually merge together. Curves 2 (solid) correspond to the temperature profiles in the case of the superhigh-frequency-radiation source at initial bed pressures of $p_0 = 5$ and 10 MPa (the upper solid curve 2 corresponds to the higher initial bed pressure).

The pressure profiles in the decomposition zone are given in Fig. 4 on the left. Curve 1 (dashed) corresponds to the case of the thermal source at $p_0 = 5$ MPa, and curve 1 (solid) corresponds to the case of the superhigh-frequency-radiation source at the same pressure. Curves 2 (dashed and solid respectively) describe the cases of the thermal source and the superhigh-frequency-radiation source at p_0 = 10 MPa. The source strength is taken to be $Q = 10^4$ W/m.

CONCLUSIONS

The analytical solutions obtained show that the value of a thermal shock in the vicinity of impermeable boundaries exposed to radiation is determined by the initial state of a porous medium partially filled with gas hydrate. As far as the destruction of gas-hydrate deposits in the porous medium is concerned, the supply of energy by electromagnetic radiation is more efficient than the regular supply of heat by conduction in the case of the same strength of the radiators.

NOTATION

ν, hydrate-saturation of the porous medium; v_{liq}, velocity of the liquid, m/sec; $m_{(i)}$, "living" porosity; $\rho_{g(i)}$, true density of the gas, where the subscript i = 1 or 2 in the brackets corresponds to the parameters of the first or second zones, kg/m^3; t, time, sec; r, coordinate, m; $v_{g(i)}$, true velocity of the gas, m/sec; $c_{(i)}$, heat capacity of the entire system, J/(kg·K); $T_{(i)}$, temperature, K; c_g, specific heat of the gas medium at constant pressure, J/(kg·K); $\lambda_{(i)}$, thermal conductivity of the system, kg·m/(sec^3·K); $p_{(i)}$, pressure, Pa; $u_{g(i)}$, rate of filtration of the gas, m/sec; $k_{(i)}$, absolute-permeability factor, m^2; $\mu_{g(i)}$, dynamic viscosity of the gas, Pa·sec; R_g, gas constant, J/(kg·K); m, porosity of the medium; $S_{g(i)}$, gas saturation; $S_{\text{liq}(i)}$, water saturation; $\rho_{(i)}$, average density of the entire system, kg/m^3; ρ_j, true densities where the subscript j = sk denotes the skeleton, j = h denotes the gas hydrate, and j = liq denotes the water, kg/m^3; l, specific heat of decomposition of the gas hydrate, J/kg; q, radiation-absorption intensity per unit area of the phase-transition surface, W/m^2; T_*, empirical parameter dependent on the form of gas hydrate, K; $p_{(s)0}$, equilibrium pressure corresponding to the initial temperature, Pa; Q, radiation intensity for the linear source per its unit length, W/m; Q_c, constant intensity of the rate of flow of the gas, kg/(m·sec); $\aleph^{(p)}$, piezoconductivity, m^2/sec; $\aleph^{(T)}$, thermal diffusivity, m^2/sec; ξ, self-similar variable (meters for the plane one-dimensional problem, dimensionless for the radial-symmetric problem). Subscripts: 0, undisturbed state; (s), value of the parameter between the zones; e, value of the parameter at the boundary of the porous medium; n = 0 or 1, plane one-dimensional or radial problem; c, constant; sk, skeleton; g, mass concentration of the gas in the gas hydrate; liq, liquid; h, hydrate. Superscript: 0, true value of the parameter.

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