Decomposition of Methane Hydrate with Heat Exposure

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Abstract. The paper presents a mathematical model of dissociation of methane hydrate during thermal exposure to a porous layer. The problem of the impact of a heat source (hot fluid) on a porous reservoir of finite length, initially saturated with methane hydrate, is considered. The temperature distributions in the system are constructed at different points in time. The influence of the temperature of the heat source on the nature of the movement of the phase transition boundary is investigated.

1. Introduction
Today, gas hydrates are the only source of natural gas on earth that can compete with traditional natural deposits. This is one of the most promising energy resources, having a wide distribution, shallow occurrence. According to various estimates, the global reserves of hydrocarbons in the composition of hydrates several times exceed the reserves of ordinary natural gas. Most (about 98%) of the deposits are found in sediments of the World Ocean, the rest (2%) - in the permafrost zone [1 – 11].

In addition, a special interest in gas hydrates is due to their thermophysical properties: The hydrate can be in a metastable state for a long time, both at positive and at negative temperatures. At present, when studying the processes of formation and decomposition of gas hydrates in porous structures, mathematical modeling is intensively used. In describing such phenomena, the methods and equations of the mechanics of multiphase systems are used [4].

Mathematical modeling of the dissociation of hydrates is considered in [5]. It has been shown that even a small thermal effect can lead to an increase in pressure, therefore this thermophysical property of the hydrate is of particular interest.

The purpose of this study is to build a mathematical model that describes the process of decomposition of the hydrate. In this paper, the process of dissociation of a gas hydrate in a porous medium of finite length is investigated during heating of a porous medium filled with hydrate in the initial state. In addition, the effect of coolant temperature on the rate of hydrate decomposition was investigated.

2. Mathematical model
Suppose that there is a porous layer of length L, containing methane gas hydrate in its composition. We will solve the problem in a flat one-dimensional approximation. We take the initial pressure $p_0$ and the temperature $T_0$ of the system corresponding to the conditions for the stable existence of methane.
hydrate, i.e. $T_0 < T_i (p_0)$, where $T_i (p)$ is the equilibrium temperature corresponding to pressure $p$.

Let the left boundary of the reservoir have a heat source in the form of a liquid (hot water), the temperature of which is maintained constant during the entire dissociation process. This boundary is impermeable to gas and water. We assume that $T_i > T_i (p_0)$. As a result of heat exposure, two areas are formed in the reservoir: the near one, saturated with hydrate decomposition products (gas and water) and the far, containing hydrate in its composition. In this case, a mobile phase transition boundary occurs, moving inland and on which the gas hydrate dissociates.

The process of heat and mass transfer in porous media is characterized by a single-temperature model. Take the porosity constant; the skeleton of the porous medium, hydrate and water is incompressible and immobile; the gas is perfect [6–8]:

$$m, \rho_{sk}, \rho_h, \rho_w = \text{const}; \quad \nu_{sk} = \nu_h = \nu_w = 0; \quad p = \rho_g R_g T.$$  

Here $m$ – porosity, $\rho_j$ and $\nu_j$ (j = g, sk, h, w) – accordingly, the true density and velocity of the j-th phase; $p$ – pressure; $T$ – temperature; $R_g$ – gas constant. The subscripts $sk, h, w, g$ correspond to the parameters of the skeleton, hydrate, water and gas. Hydrate is considered a two-component system with a mass concentration of gas $G$.

To describe the process of dissociation of hydrate, we use the laws of conservation of mass and heat and Darcy’s law [4]:

$$\frac{\partial}{\partial t}(mS_g \rho_g) + \frac{\partial}{\partial x}(mS_g \nu_g \rho_g) = 0,$$  

(1)

$$\rho c \frac{\partial T}{\partial t} + \rho_g c_g mS_g \nu_g \frac{\partial T}{\partial x} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right),$$  

(2)

$$mS_g \nu_g = \frac{k_g}{\mu_g} \frac{\partial p}{\partial x}.$$  

(3)

Here $x$ – spatial coordinate, $t$ – time; $S_j$ (j = g, w, h) – pore saturation with j-th phase ($\sum_j S_j = 1$); $c_g, \nu_g, k_g$ and $\mu_g$ – specific heat, velocity, permeability and dynamic viscosity of the gas phase; $\rho c$ and $\lambda$ – accordingly, the specific volumetric heat capacity and thermal conductivity of the system, which we will consider to be constant values, since they are mainly determined by the parameters of the skeleton.

The conditions on the moving phase transition boundary following from the laws of conservation of mass and heat for the considered problem are:

$$mS_{w(l)} \rho_w \dot{x}_w = m\rho_h (1 - G) \dot{x}_h, \quad mS_{g(l)} \rho_g (\nu_{g(l)} - \dot{x}_w) = mG \rho_h \dot{x}_w,$$  

(4)

$$\lambda \frac{\partial T_{w(l)}}{\partial x} = m\rho_h L_h \dot{x}_w,$$  

(5)

here $T_{w(l)}, S_{w(l)}$ and $S_{g(l)}$ – respectively, temperature, water saturation and gas saturation of the first region; $L_h$ – specific heat of hydrate decomposition, $\dot{x}_w$ – the speed of movement of the phase transition boundary. From the first equation of system (4) we get:

$$S_{w(l)} = \frac{\rho_h (1 - G)}{\rho_w}, \quad S_{g(l)} = 1 - S_{w(l)}.$$  

(6)

According to the formulation of the problem under consideration, we will assume that the pressure in the reservoir is constant and equal to the initial pressure $p_0$ of the system. In this case, the temperature in the region containing methane hydrate is also constant and equal to the initial temperature $T_0$ of the system. Therefore, to determine the temperature field in the first region, we use the equation that follows from (2) and taking into account (3):

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right).$$  

(7)
The initial and boundary conditions for (7) are:

\[ t = 0: \quad T = T_0 \quad (0 \leq x \leq L), \]

\[ t > 0: \quad T = T_e \quad (x = 0), \]

\[ t > 0: \quad T = T_0 \quad (x = x_e). \]

The condition for determining the coordinates of the moving boundary follows from (5).

To solve (7) with the initial and boundary conditions (8) - (9) and condition (5), we use the method of catching a moving front into a node of a spatial grid. In this case, equations (5), (7) - (9) are represented as implicit finite-difference analogues; the solution of the system of algebraic equations at each time layer is carried out by the method of sweep and iteration until reaching a given convergence.

3. Calculations results

Based on the solution of the problem, a graphic illustration of the temperature distribution at various points in time has been constructed. The integration of the system was carried out with the following parameters: \( T_e = 280 \text{ K}, \ T_0 = 274 \text{ K}, \ p_0 = 5 \text{ MPa}, \ k_0 = 10^{-14} \text{ m}^2, \ m = 0.2, \ G = 0.12, \ \mu_k = 10^{-5} \text{ Pa} \cdot \text{s}, \)

\( \lambda = 2 \text{ W/(m} \cdot \text{K}), \ L_h = 5 \cdot 10^5 \text{ J/kg}, \ \rho C = 2.5 \cdot 10^6 \text{ J/(K} \cdot \text{m}^3), \ L = 20 \text{ m}. \) The parameters \((p_0, T_0)\) and \((p_0, T_e)\) were chosen in such a way as to correspond to the conditions for the stable existence of the hydrate and the stable existence of the mixture of gas and water. As follows from fig. 1, the temperature in the near field varies linearly. In this case, with the passage of time, heating of the layers located deep in the formation is observed.

![Figure 1. Reservoir temperature distribution for times: 1 – t = 5 day; 2 – t = 15 day.](image)

Figure 2 shows the law of motion of the phase transition boundary at two different temperatures on the left boundary. As follows from the figure, over time, the speed of movement of the phase transition boundary decreases. This is explained by the fact that the dissociation process is limited by the supply of heat to the phase transition front, which decreases with time. In this case, an increase in temperature \( T_e \) increases the rate of hydrate decomposition, which manifests itself at large times after the action of the heat source.
Figure 2. The dependence of the phase transition boundary on time: 1 – $T_e = 280$ K; 2 – $T_e = 282$ K.

4. References
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