Estimation of efficiency of the thermal method in the development of gas-hydrate deposits

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Abstract. In the work on the basis of the proposed mathematical model, the process of decomposition of methane hydrate under thermal action on the reservoir is numerically investigated. Based on the calculations, it was shown that the energy efficiency of the decomposition of methane hydrate, i.e. the ratio of the energy obtained by burning the released methane to the energy spent on heating the formation decreases with increasing temperature of the coolant. The formation temperature distributions are also presented and the dependences of the position of the phase transition boundary on the system parameters are investigated. The problem is solved in a plane-one-dimensional formulation. According to the proposed scheme, a homogeneous porous layer of finite length, containing methane hydrate in the initial state, is considered. In this problem, we believe that the decomposition of hydrate into water and gas occurs at the boundary of phase transitions.

1. Introduction

Gas hydrates are currently giant storages of natural gas, mainly methane, the occurrence of which is tied to offshore deposits, where fairly low temperatures and high pressures are realized. Thus, according to studies [1,2], in 1 m³ of methane hydrate up to 165 m³ of methane can be contained under normal conditions. Experimental studies of the processes of formation and decomposition of gas hydrates were considered in [3]. Theoretical studies of the formation and decomposition of hydrates in porous formations are discussed, in particular, in [4–7]. One of the methods of gas production from the gas hydrate is the thermal method, the essence of which is to supply hot coolant to the gas hydrate formation, as a result of which the gas hydrate decomposes into gas hydrate and water. In the present work, in the plane-one-dimensional approximation, we consider the problem of decomposition of methane hydrate completely saturating a porous medium as a result of exposure to a coolant. Issues of modeling the process of decomposition of gas hydrates are discussed in [9–11].

The energy efficiency of this method is investigated and the dependences of the position of the phase transition boundary on the system parameters are investigated [12].

2. Materials and methods

The conditions for the formation and decomposition of gas hydrates are depicted using phase diagrams in the coordinates "temperature - pressure". For most gas hydrates, the condition of three-phase equilibrium between the hydrate-forming gas, its gas hydrate and water is satisfactorily described by the dependence:
\[ T_r = T_{r0} + T, \ln \left( \frac{p}{p_{r0}} \right); \]  

Equilibrium hydrate formation temperatures corresponding to pressures \( p \) and \( p_{r0} \). \( T_r \) are an empirical parameter. In particular, for methane hydrate from the equilibrium curve, \( T_{r0} = 280 \) K, \( p_{r0} = 5.5 \) MPa.

Let us consider a porous layer of length \( L \), the pores of which are completely saturated with methane hydrate. The initial pressure will be assumed equal to \( p_0 \), the initial temperature of the system will be determined by the condition of phase equilibrium, i.e., \( T_0 = T_r(p_0) \). Assuming that the pressure change in the system is insignificant, i.e., \( p = p_0 = \text{const} \), we assume that in there are two areas in the reservoir: the nearest, adjacent to the left boundary of the formation and saturated with methane and water, and the distant, adjacent to the right boundary of the formation and containing methane hydrate. In addition, a mobile boundary of phase transitions \( x = x(t) \) arises, separating the above regions and moving deep into the reservoir.

When describing heat and mass transfer processes accompanied by decomposition of methane hydrate, we will accept the following assumptions: porosity is constant, the skeleton of the porous medium, hydrate and water are incompressible and motionless, the gas is calorically perfect [8]:

\[ m, \rho_{sk}, \rho_{h}, \rho_{w} = \text{const}; \ u_{sk} = u_{h} = u_{w} = 0; \ p = \rho_{g} R_{g} T \]

Here \( m \) is the porosity, \( \rho_{j} \) and \( u_{j} \) \((j = g, sk, h, w)\) are the true density and velocity of the \( j \)-th phase, respectively; \( p \) is the pressure; \( T \) is the temperature; \( R_{g} \) is the gas constant. The subscripts \( sk, h, w \) and \( g \) correspond to the parameters of the skeleton, hydrate, water and gas. Hydrate is considered a two-component system with a mass concentration of gas \( G \).

The system of basic equations for the near field, including the equations of continuity and heat influx, under the assumptions noted above, has the form:

\[ \frac{\partial}{\partial t} \left( mS_{g}\rho_{g} \right) + \frac{\partial}{\partial x} \left( mS_{g}\rho_{g} u_{g} \right) = 0, \]

\[ \rho_{c} \frac{\partial T}{\partial t} + \rho_{g} c_{g} mS_{g} u_{g} \frac{\partial T}{\partial x} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right). \]

Here \( S_{g}, u_{g}, \) and \( c_{g} \) are the pore saturation, velocity, and specific heat of the gas phase, respectively; \( \rho_{c} \) and \( \lambda \) are the specific volumetric heat capacity and the thermal conductivity of the system. Since the main contribution to the values of \( \rho_{c} \) and \( \lambda \) is made by the corresponding skeleton parameters of the porous medium, we will consider them to be constant values.

The temperature in the far region saturated with methane hydrate will be assumed constant equal to the initial temperature of methane hydrate.

In addition, we supplement the system of equations (2) and (3) by the relations following from the conditions of mass and heat balance at the phase transition boundary \( x = x(t) \):

\[ mS_{w(1)} \rho_{w} \dot{x}_{(1)} = m\rho_{h} (1 - G) \dot{x}_{(1)} , \quad mS_{g(1)} \rho_{g(1)} (u_{g(1)} - \dot{x}_{(1)}) = mG \rho_{h} \dot{x}_{(1)} , \]

\[ \lambda \frac{\partial T_{(1)}}{\partial x} = - \rho_{h} L_{h} \dot{x}_{(1)} , \]

Here \( L_{h} \) is the specific heat of hydrate decomposition, \( \dot{x}_{(1)} \) - the velocity of the phase transition boundary; the subscript \( i = 1 \) corresponds to the parameters of the near field. From the first equation of system (4) to determine the values of water and gas saturation for the near field, we get:
Since changes in the temperature $\Delta T$ of the formation associated with the dissociation of the hydrate are small compared to its initial temperature $T_0$, i.e. $\Delta T \ll T_0$ and in accordance with the assumption of a constant pressure in the system, we find that the true density of the gas phase is a constant and equal to:

$$\rho_g = \frac{P_0}{R_g T_0}.$$  

Then, based on the continuity equation (2), the velocity $v_g$ of the gas phase through the cross section determined by the $x$ coordinate can be obtained from the following relation:

$$v_g = v_{r(i)}$$  \hspace{1cm} (5)

where $v_{g(i)}$ is the gas velocity at the boundary of the phase transition.

The initial conditions and conditions on the external boundaries of the reservoir are presented in the form:

$$t = 0: \quad p = p_0, \quad T = T_c(p_0) \quad (0 \leq x \leq L);$$

$$t > 0: \quad p = p_0, \quad T = T_e \quad (x = 0);$$

$$t > 0: \quad p = p_0, \quad T = T_0 \quad (x = x_{i(i)}).$$  \hspace{1cm} (6)

The presented system (2) – (4) is closed. To solve it, the method of catching the front into the spatial mesh node is used. The essence of this method is that for an unknown and determined in the course of solving the problem time step, the front of the phase transition moves along the grid also by one spatial step.

3. Calculations results

For different times, Figure 1 shows the temperature distribution in the formation with a length of $L = 100$ m at a coolant temperature of $T_c = 286$ K. The initial pressure was assumed to be $p_0 = 6$ MPa, the initial temperature, in accordance with (1), $T_0 = 280.87$ K. The following values are accepted for the remaining parameters characterizing the system: $m = 0.15$, $G = 0.12$, $\rho_h = 900$ kg/m$^3$, $\rho_w = 1000$ kg/m$^3$, $R_g = 520$ J/(K·kg), $\lambda = 2$ W/(m·K), $c_g = 2600$ J/(K·kg), $L_h = 5 \cdot 10^5$ J/kg. As follows from the figure, over time, the heat received from the well mainly goes to the warming of the frontline area.

**Figure 1.** The temperature distribution in the reservoir for a point in time: $1 - t = 20$ days; $2 - t = 50$ days; $3 - t = 100$ days.
Dependences of the coordinate of the phase transition front $x = x(s)$ on time are presented. Line 1 corresponds to the temperature of the coolant $T_e = 285$ K, line 2 – $T_e = 295$ K. As follows from the figure, with an increase in the temperature of the coolant, the velocity of the front of the phase transition increases. This is due to the fact that with an increase in $T_e$, the intensity of the hydrate dissociation process increases.

![Figure 2](image)

**Figure 2.** The dependence of the coordinate of the front of the phase transition from time to time: 1 – $T_e = 285$ K; 2 – $T_e = 295$ K

Of particular interest is the determination of the energy efficiency of the thermal method of gas extraction from the gas hydrate composition. We define energy efficiency $\kappa$ in the form of:

![Figure 3](image)

**Figure 3.** The dependence of the energy efficiency of the thermal method from time to time: 1 – $T_e = 285$ K; 2 – $T_e = 295$ K.

Dependences of energy efficiency on time are presented. Lines 1 and 2 correspond to the temperature of the coolant $T_e = 285$ K and $T_e = 295$ K. From the figure it follows that the energy efficiency of gas extraction at the initial stage of the process decreases, which is associated with the heating of in-situ areas. Moreover, with decreasing temperature of the coolant, energy efficiency increases.

4. **Conclusion**

The problem of the possibility of decomposition of a gas hydrate formation upon thermal exposure in a plane-one-dimensional formulation with a frontal boundary of phase transitions is solved. For this approximation, solutions are constructed that describe the temperature fields, as well as the dynamics of the hydrate decomposition boundary and the gas mass flow rate. The influence of the temperature
difference between the formation and the injected water on the evolution of the hydrate decomposition front and on the energy efficiency of methane hydrate decomposition at different porosity of the formation was studied. The proposed calculation scheme and the results obtained on its basis allow us to analyze the efficiency of hydrate formation development by heating the working zone of the field. A quantitative assessment was made of the effectiveness of the thermal methane extraction method with a change in the heating temperature and pressure drop.

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