



The mathematical model of the gas hydrate deposit development in permafrost



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ABSTRACT

This paper presents the mathematical model of the gas extraction from a reservoir initially saturated with methane and its hydrate, under conditions of negative (below 0 °C) initial temperature of the reservoir. The algorithm is proposed and the numerical scheme is constructed which makes it possible to find the main parameters of the nonisothermal filtration flow in a hydrate-saturated reservoir, taking into account the hydrate decomposition to gas and ice. The analysis of the influences of the mass flow rate of gas extraction, the porous medium permeability, the initial reservoir temperature, and the initial hydrate saturation on the regime and rate of the gas hydrate decomposition was carried out.

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1. Introduction

Natural gas is one of the main energy carriers, for example, in 2014 it accounts for 21.6% of the world's electricity production, and its share continues to grow [1]. The main component of natural gas is methane (77–99%). The largest reserves of methane are concentrated in the hydrated state. Their total volume (≈ 20000 trillion m^3) is two orders of magnitude higher than the volume of traditional methane recoverable reserves (≈ 250 trillion m^3), and methane hydrate contains more than 50% of carbon from total known world hydrocarbon reserves [2]. Thus, given the increasing demand and the largest amount of fossil fuels in nature, methane from gas hydrates is the most promising source of energy [3,4].

The extraction of methane from gas hydrates causes difficulties due to their solid form. Existing methods rely on dissociation, in which gas hydrates decompose to components [2,4]. The main methods for developing gas hydrate deposits include: pressure reduction, heating and inhibitor injection. The technology of replacement of methane in hydrates by carbon dioxide is attracting attention [5–8]. At the pressure drop method of the gas hydrate deposits development, it is necessary that the pressure in the reservoir becomes lower than the equilibrium hydrate decomposi-

tion pressure. In this case the gas hydrate begins to decompose to gas and water (ice) absorbing heat. If the hydrate decomposition occurs to gas and ice then the energy costs of the gas hydrate deposits developing are lower than in the case when the hydrate decomposition occurs to gas and water, since the specific heat of the phase transition hydrate \leftrightarrow ice and gas (≈ 160 kJ/kg) is much lower than the heat of the phase transition hydrate \leftrightarrow water and gas (≈ 430 kJ/kg) [9,10]. Of course, this option is only applicable for deposits with the thermodynamic conditions allow the existence of ice.

The importance of a theoretical study of the pressure drop method for the gas hydrate deposits development is quite obvious. The results obtained in this study significantly reduce the quantity of necessary experimental and field data, and the clear view of the studied processes makes it possible to effectively control them [7,11].

The mathematical models of the process of the gas hydrate decomposition in a porous medium to gas and water (ice) are presented in the works [10,12–17]. In these works analytical solutions of this problem are constructed and, in particular, showed that two regimes are possible: with the frontal surface or with the extended zone of the gas hydrate dissociation. But in the majority of the works analytical solutions were obtained for the case when the phase transitions occurs at the frontal surface, which gives an adequate mathematical description only for a limited range of parameters characterizing the state of the system and the intensity of the

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impact on the reservoir, namely, at the low gas extraction rates and the low permeability of porous media. In this paper, we propose the mathematical model of the gas hydrate decomposition in the case of a negative (below 0 °C) initial reservoir temperature (before the start of well operation). This model takes into account the main features of the process: nonisothermal gas filtration, phase transitions, real gas properties, adiabatic cooling effect, Joule-Thomson effect. Numerical solutions of the problem of the methane hydrate decomposition in a porous medium with both the frontal surface and extended zone of phase transitions are obtained.

2. Mathematical model

Let us consider the problem of the gas extraction from the horizontal reservoir of a limited size r_k , the top and bottom of which are impenetrable (Fig. 1). We assume that the reservoir is homogeneous and isotropic, and also neglect the influence of the upper and lower boundaries. Then we can assume that the problem is one-dimensional and the parameters of filtration flow depend only on the radial coordinate r and time t . Let the reservoir in the initial state is saturated with gas and its hydrate, the pressure p_0 and temperature T_0 of which correspond to the thermodynamic conditions of the hydrate stability:

$$t = 0, r \in [r_w, r_k]: \quad T = T_0 < 0^\circ\text{C}, \quad p = p_0, \quad S_h = S_{h0}, \\ S_g = 1 - S_{h0},$$

where p is the pressure; T is the temperature; r_w and r_k are the well and reservoir radiuses; S_j ($j = i, h, g$) is the saturation of pores with j -th phase (i – ice, h – hydrate, g – gas); S_{h0} is the initial hydrate saturation. The coordinate r starts from the central axis of the well.

At the left border of the reservoir ($r = r_w$) through the well, which has opened the reservoir for the entire thickness, the gas extraction with a constant mass flow rate Q (per unit of the well height) begins:

$$t > 0, r = r_w: \quad r \frac{\partial p^2}{\partial r} = Q \frac{z_g \mu_g R_g T}{\pi k S_g^3}, \quad \frac{\partial T}{\partial r} = 0. \tag{2.1}$$

Here k is the reservoir absolute permeability; μ_g and z_g are the dynamic viscosity and the gas compressibility factor; R_g is the specific gas constant.

It is also possible to specify another boundary condition, namely: through the well which has opened the reservoir for the entire thickness, gas is extracted at a constant bottomhole pressure p_w :

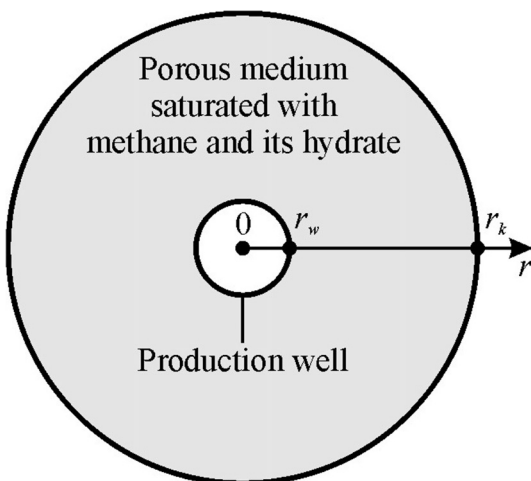


Fig. 1. Scheme of the modeling area.

$$t > 0, r = r_w: \quad p = p_w < p_0, \quad \frac{\partial T}{\partial r} = 0. \tag{2.2}$$

At the gas extraction, the pressure in the reservoir begins to decrease and, correspondingly, when this pressure decreases below the equilibrium pressure of hydrate formation, the gas hydrate decomposes. Fig. 2 shows the phase diagram for the H₂O-CH₄ system. In this diagram, the g-i-h and g-w-h lines determine the three-phase equilibria of the systems “methane-ice-hydrate” and “methane-water-hydrate”, “gas-water-hydrate”, and line i-w is two-phase “water-ice” equilibrium. The lines g-i-h and g-w-h correspond to the equilibrium parameters of the gas hydrate decomposition to ice and water, respectively.

At the gas extraction, the hydrate decomposition takes place due to pressure drop below equilibrium. And three characteristic zones can appear in the reservoir (Fig. 3): the near (the first zone), in this zone the reservoir pores saturated with gas and ice; the intermediate (the second zone), in this zone gas, ice and hydrate are in equilibrium; and the far (the third zone), in this zone the reservoir pores saturated with methane and its hydrate. Accordingly, the gas hydrate dissociation begins at the surface between the second and third zones ($r = r_{(d)}$), and ends at the boundary between the first and second zones ($r = r_{(n)}$). The initial hydrate saturation (S_{h0}) is equal to the hydrate saturation of the third zone and is constant at all points of this zone.

The conditions for temperature and pressure at the right boundary are following:

$$t > 0, r = r_k: \quad \frac{\partial p}{\partial r} = 0, \quad \frac{\partial T}{\partial r} = 0.$$

At the modelling, we assume the following assumptions: the hydrate is a two-component system with a constant mass concentration of gas G ; the temperatures of the porous medium, gas, hydrate and ice at each point of the reservoir are equal; the reservoir porosity m is constant; the porous medium skeleton, gas hydrate and ice are incompressible and immobile.

The system of basic equations describing the processes of filtration and heat transfer in a porous medium, representing the laws of conservation of masses (2.3), (2.4) and energy (2.6), Darcy’s law (2.5) and the equation of state for a gas (2.7). This system in the radial case taking into account accepted assumptions has the form [10,18–20]:

$$\frac{\partial}{\partial t} (\rho_g S_g + \rho_h S_h G) + \frac{1}{r} \frac{\partial}{\partial r} (r \rho_g S_g v_g) = 0, \tag{2.3}$$

$$\frac{\partial}{\partial t} (\rho_i S_i + (1 - G) \rho_h S_h) = 0, \tag{2.4}$$

$$m S_g v_g = - \frac{k_g}{\mu_g} \frac{\partial p}{\partial r}, \tag{2.5}$$

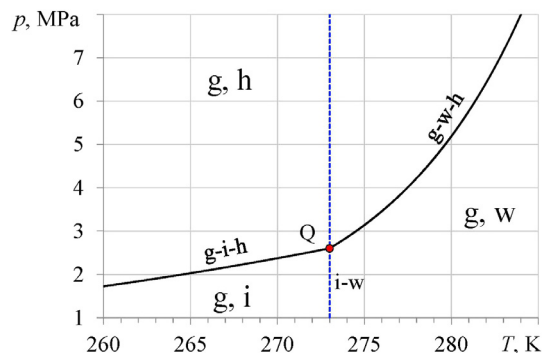


Fig. 2. Phase diagram of the «H₂O-CH₄» system.

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