Numerical research of gas-hydrate deposit development in the conditions of negative temperatures

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Abstract. Numerical research of non-isothermal filtration flow in a hydrate saturated reservoir taking into account the decomposition of methane hydrate is carried out. It is established that the gas extraction in the case of the negative initial reservoir temperature (the gas hydrate decomposition occurs to gas and ice) is more beneficial than the methane extraction from the reservoir with the positive initial temperature (the methane hydrate decomposition occurs to gas and water). Calculations show that, in the first case, the time for the complete hydrate decomposition in a reservoir decreases with an increase in the initial reservoir temperature and an increase in the bottomhole depression.

1. Introduction

At present, there is an increase in the cost of natural gas production, which occurs against the background of growing demand for this raw material \cite{1}. Accordingly, there is growing interest in the industrial development of non-traditional sources of hydrocarbons. Significant potential resources of natural gas (primarily methane) are in the deposits of gas hydrates \cite{2, 3}. To date, over two hundred gas hydrate deposits have been discovered in the world. On the continents these deposits are confined mainly to the areas of permafrost \cite{1, 4}. In the gas hydrates a huge volume of natural gas is concentrated, according to some estimates this volume several times greater than the volume of natural gas in free state \cite{2, 3}. Industrial extraction of only 15\% of methane from hydrate-containing deposits will provide the world with energy for 200 years at the current level of the gas consumption \cite{3}.

When developing deposits of gas hydrates it is necessary to transfer gas in a reservoir from the solid hydrate state to the free gas state. Then, methane is removed from the reservoir using traditional gas production technologies \cite{1, 5}. At present, several methods are proposed for extracting methane from gas hydrate deposits: pressure reduction, heating, inhibitor input, injection of carbon dioxide into a reservoir. With the depressive method of the gas hydrate deposits development it is necessary that the pressure in a reservoir becomes lower than the equilibrium hydrate decomposition pressure. In this case, gas hydrate begins to dissociate to gas and water (or ice) with the heat absorption. It should be noted that any technological ideas and appropriate schemes for the hydrocarbon deposits development should be supported by appropriate theoretical calculations \cite{6, 7}.

Theoretical researches of the gas extraction from a hydrate saturated reservoir are presented in a number of works, for example \cite{8-11}. In this paper, we present the numerical research results of the process of the gas extraction from a reservoir initially saturated with methane and its hydrate under conditions of negative (lower than 0°C) initial temperature of the reservoir.
2. Main equations

Let a horizontal porous reservoir of constant thickness be filled with methane and its hydrate in the initial state, the reservoir pressure \( p_0 \) and temperature \( T_0 \) correspond to the thermodynamic conditions of gas and hydrate existence in free state. The initial hydrate saturation \( S_{h0} \) is known. Let the roof and bottom of the reservoir be impenetrable. We assume that the reservoir is homogeneous and isotropic, and also we neglect the influence of the upper and lower boundaries. In this connection, we can assume that the problem is one-dimensional and the process parameters depend only on the spatial coordinate \( x \) and time \( t \) [12].

We accept the following assumptions: methane hydrate is a two-component system with a constant mass concentration of gas \( G \); the temperature of porous medium, gas, methane hydrate and ice (or water) at each point of the reservoir coincide (single-temperature process); the reservoir porosity \( m \) is constant; the porous medium skeleton, gas hydrate and ice (or water) are incompressible and immobile.

Initial and boundary conditions can be written in the following form:

\[
\begin{align*}
\left. \begin{array}{l}
\left( 0, x, x \right) = \left( 0, x, L \right) = \left( 0, L \right), \\
\end{array} \right\} \\
\left. \begin{array}{l}
t = 0, x \in [0, L] : \quad T = T_0, \quad p = p_0, \quad S_h = S_{h0}, \quad S_g = 1 - S_{h0}, \\
\end{array} \right\} \\
\left. \begin{array}{l}
t > 0, x = 0: \quad p = p_c < p_0, \quad \frac{\partial T}{\partial x} = 0, \\
\end{array} \right\} \\
\left. \begin{array}{l}
t > 0, x = L: \quad \frac{\partial p}{\partial x} = 0, \quad \frac{\partial T}{\partial x} = 0.
\end{array} \right\}
\end{align*}
\]

Here \( L \) is the reservoir length; \( S_j (j = i, h, g) \) is the pore saturation with \( j \)-th phase (\( g \) – gas, \( i \) – ice, \( w \) – water, \( h \) – gas hydrate).

The system of main equations consists of the equations of conservation of mass and energy, the Darcy law and the equation of gas state. This system in the rectilinear-parallel approximation has the form [10, 12, 13]:

\[
\begin{align*}
\frac{\partial}{\partial t} \left( \rho_g S_g + \rho_h S_h G \right) + \frac{\partial}{\partial x} \left( \rho_g S_g v_g \right) &= 0, \\
\frac{\partial}{\partial t} \left( \rho_i S_i + (1 - G) \rho_h S_h \right) &= 0, \\
\rho_h c_h v_h = -\frac{k_g}{\mu_g} \frac{\partial p}{\partial x}, \quad k_g = k S_g^3, \\
\rho c_T \frac{\partial T}{\partial t} &= \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial t} (\rho h L_h S_h) - \rho_g c_g m S_g v_g \left( \frac{\partial T}{\partial x} + \varepsilon \frac{\partial p}{\partial x} \right) + \rho_p c_p m S_p \eta \frac{\partial p}{\partial t}, \\
p &= z p_c R_g T, \quad z = \left[ 0.17376 \cdot \ln(T/T_c) + 0.73 \right]^{p/p_c} + 0.1 \cdot p / p_c,
\end{align*}
\]

where \( \rho_j \) and \( c_j (j = g, i, h) \) are the density and specific heat of the \( j \)-th phase; \( \rho_{oh}, \lambda_{oh} \) and \( c_{oh} \) are the density, thermal conductivity and specific heat of the porous medium skeleton; \( v_g \) and \( \mu_g \) are the velocity and dynamic viscosity of gas phase; \( k \) is the absolute reservoir permeability; \( \varepsilon \) and \( \eta \) are the throttling factor and adiabatic coefficient; \( L_h \) is the heat of hydrate decomposition; \( \rho c \) and \( \lambda \) are the specific volume heat capacity and coefficient of thermal conductivity of the system "reservoir – saturating substance"; \( T_c \) and \( p_c \) are the empirical critical parameters of gas.

The values of temperature and pressure in the region of the hydrate decomposition are related by the condition of phase equilibrium [14, 15].
3. Calculation results

In the work, a numerical solution of the system of equations was carried out on the basis of the algorithm previously proposed by the authors [16]. During the calculations the following values of the used parameters were adopted: \( L = 500 \text{ m} \); \( m = 0.1 \); \( k = 10^{-14} \text{ m}^2 \); \( S_h = 0.2 \); \( p_c = 4.6 \text{ MPa} \); \( T_c = 190.56 \text{ K} \); \( c_{sk} = 1000 \text{ J/(kg·K)} \); \( c_h = 2100 \text{ J/(kg·K)} \); \( c_i = 2060 \text{ J/(kg·K)} \); \( c_w = 4200 \text{ J/(kg·K)} \); \( \lambda_{sk} = 1.5 \text{ W/(m·K)} \); \( \lambda_h = 0.5 \text{ W/(m·K)} \); \( \lambda_i = 2.2 \text{ W/(m·K)} \); \( \lambda_w = 0.58 \text{ W/(m·K)} \); \( R_g = 518.3 \text{ J/(kg·K)} \); \( \rho_{sk} = 2000 \text{ kg/m}^3 \); \( \rho_h = 900 \text{ kg/m}^3 \); \( \rho_i = 900 \text{ kg/m}^3 \); \( \rho_w = 1000 \text{ kg/m}^3 \); \( G = 0.12 \); the space coordinate step \( \Delta r = 1 \text{ m} \); the time step \( \Delta t = 600 \text{ s} \); the values \( c_g \), \( \lambda_g \), \( \mu_g \) were determined by interpolating table data for methane [2, 16-18]. Assume that the width of the reservoir is 50 m, and its thickness is 20 m.

Initial reservoir parameters when the gas hydrate decomposes into gas and ice – \( p_0 = 2.8 \text{ MPa}, T_0 = 270 \text{ K} \); into gas and water – \( p_0 = 3.8 \text{ MPa}, T_0 = 276 \text{ K} \).

Figure 1 shows the time distribution of the value of the accumulated gas production at the different values of the bottomhole depression (\( \Delta p = p_0 - p_e \)). Two cases are considered: 1) the initial reservoir temperature \( T_0 < 0°C \), and the decomposition of the gas hydrate occurs to gas and ice (\( L_{hi} = 166 \text{ kJ/kg} \)); 2) \( T_0 > 0°C \), and the decomposition of the gas hydrate occurs to gas and water (\( L_{hw} = 430 \text{ kJ/kg} \)). The solid lines correspond to the first case; the dashed lines correspond to the second case. For the second case ("gas hydrate \( \rightarrow \) gas + water") the temperature in the reservoir did not drop below 0°C.

Figure 1. The change in time of the accumulated gas production.

Lines 1, 3 and 5 – decomposition of gas hydrate to gas and ice at the bottomhole depressions \( \Delta p = 0.3, 0.6 \) and \( 0.9 \text{ MPa} \), respectively.

Lines 2, 4 and 6 – decomposition of gas hydrate to gas and water at the bottomhole depressions \( \Delta p = 0.3, 0.6 \) and \( 0.9 \text{ MPa} \), respectively.

Figure 1 shows that with a small depression (lines 1 and 2) the amount of the accumulated gas production practically coincides for both cases. With this value of \( \Delta p \) there is no decomposition of gas hydrate and only free gas is taken. For large values of the reservoir depression (lines 3-6), the gas hydrate decomposes, and the amount of the accumulated gas production for the case "gas hydrate \( \rightarrow \) gas + ice" being 2-2.5 times larger than the accumulated gas production for the case "gas hydrate \( \rightarrow \) gas + water". Thus, in the realization of the first case, due to the lesser heat of the phase transition, more intensive gas hydrate decomposition takes place and, accordingly, a larger amount of gas is extracted from the reservoir.
Figure 2. The distributions in time of the percentage of undecomposed gas hydrate in the whole reservoir at the different values of depression $\Delta p$. Lines 1, 3 and 5 correspond to $\Delta p = 0.3$, $0.6$ and $0.9$ MPa, respectively (phase transition "gas hydrate $\rightarrow$ gas + ice"); lines 2, 4 and 6 – $\Delta p = 0.3$, $0.6$ and $0.9$ MPa, respectively ("gas hydrate $\rightarrow$ gas + water").

A similar conclusion can be drawn by analyzing Figure 2. It can be seen that for small values of depression (lines 1 and 2) there is no decomposition of gas hydrate. In this case, the pressure in the reservoir does not fall below the equilibrium hydrate decomposition pressure. As the value of $\Delta p$ increases (lines 3 and 4), the gas hydrate decomposes, but this process is rather slow (especially in the case "gas hydrate $\rightarrow$ gas + water"). So, for 5 years at $T_0 < 0^\circ$C (line 3) about 80% of the gas hydrate present in the reservoir has been decomposed, and this process continues. When decomposing gas hydrate to gas and water (line 4) only about 20% of the hydrate has been decomposed, and this process practically ceased after 2 years, which indicates a lack of the reservoir energy for the hydrate decomposition. The same lack of energy at $T_0 > 0^\circ$C is also observed for the large values of depression $\Delta p$ (line 6). For the case of decomposition to gas and ice at $\Delta p = 0.9$ MPa (line 5) gas hydrate completely decomposed in about 2.5 years.

Figure 3 shows the dependence of the time for the complete decomposition of gas hydrate in the whole reservoir to gas and ice on the magnitude of the depression at different values of the initial reservoir temperature. It is seen that initially an increase in the depression $\Delta p$ and an increase in the initial reservoir temperature $T_0$ ($T_0 < 0^\circ$C) lead to a significant decrease in the time of full hydrate decomposition for the case "gas hydrate $\rightarrow$ gas + ice". Further increase in the depression does not lead to significant increase in the rate of the hydrate decomposition.

4. Conclusions

Mathematical model is proposed and the features of the methane hydrate decomposition in the hydrate saturated reservoir are studied in the cases of negative and positive initial reservoir temperature. It has been established that the mode of the gas extraction with decomposition of gas hydrate to gas and ice is more profitable, because with the same depressions more gas is extracted from the gas hydrate deposit. Calculations show that the lower the initial reservoir temperature is, the longer process of the hydrate decomposition to gas and ice becomes. At the same time, an increase in depression first leads
to a significant increase in the gas hydrate decomposition rate (correspondingly to large volumes of produced gas), but with a further increase in the depression, the influence of this factor on the methane hydrate decomposition rate becomes insignificant.

Figure 3. The time of the complete methane hydrate decomposition in the whole reservoir depending on the depression magnitude. Lines 1, 2 and 3 correspond to the initial reservoir temperature $T_0 = 272, 270, 268$ K.

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