Analysis of heat transfer effects on gas production from methane hydrate by depressurization

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Jiafei Zhao [1], Di Liu [1], Mingjun Yang [2], Yongchen Song *

Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education, School of Energy and Power Engineering, Dalian University of Technology, Dalian 116024, PR China

A B S T R A C T

The dissociation of natural gas hydrates is an endothermic process. This dissociation process requires the continuous absorption of heat energy from the sediment and pore fluid. This heat transfer governs the dissociation rate and affects gas production. In this study, a two-dimensional axisymmetric simulator is developed to model the effects of heat transfer on the process of hydrate dissociation in porous media by depressurization. A series of simulations are performed to study sensible heat effects on the sediment, heat flow transfer in the cap- and base-sediment, and the effects of conductive and convective heat transfer on gas production from methane hydrate depressurization. The results show that the porous media material and the water content are two significant factors that affect the sensible heat in gas hydrate dissociation: the porous media material can increase methane hydrate dissociation, but water inhibits the dissociation process by affecting the pressure on the inner sediment. A high thermal conductivity of the sediment can initially positively affect hydrate dissociation but may later partially inhibit the process. Convective heat transfer in the gas flow increases hydrate dissociation markedly compared to that in water flow.

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1. Introduction

Methane hydrates (MH) are crystalline solids composed of water and methane gas. Methane molecules become trapped in the water cavities at low temperatures and high pressures. A 1-m^3 volume of MH can dissociate into approximately $164 m^3$ of methane and $0.8 m^3$ of water [1,2]. Methane hydrates are considered as a potential energy source because of vast MH reserves, their high energy capacity and reduced pollution from combustion. At least three exploitation methods, including depressurization, thermal stimulation, and inhibitor injection, are available for methane gas production.

Experiments and simulations have been used to predict the behavior of hydrate dissociation under different methods. Kamath and Godbole [3] developed a mathematical model for a hot-brine simulation to the compute gas recovery and energy-efficiency ratio. Kurihara et al. [4] conducted examinations of the MH dissociation and production using depressurization and thermal methods. With low initial temperatures, they found that the gas production rate by the hot water huff and puff is higher than that by depressurization at early stages of production, while the hot water huff and puff gas production rate is much lower at latter stages of production. In reservoirs with medium and high initial temperatures, the hot water huff and puff is adverse to increases in the gas production. Falser et al. [5–7] conducted experiments to increase gas production from hydrate by combining depressurization with heating of the wellbore. He found if the heat influx from the outer boundary is limited, the specific heat of the formation is rapidly used up when the wellbore is only depressurized and not heated.

One of the key requirements of any production technique is the provision of heat necessary for the endothermic hydrate dissociation reaction. The depressurization technique is the least energy intensive and most economically viable method [8,9]. In depressurization, methane hydrates dissociate when the pressure in the production well is maintained below its equilibrium value. The heat of dissociation is provided by the surrounding sediments. Selim and Sloan [10] and Hong et al. [11,12] have proposed that depressurization be used when the thermal conditions of the

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* Corresponding author. Address: School of Energy and Power Engineering, Room 312, Dalian University of Technology, Dalian, Liaoning 116024, PR China. Tel.: +86 411 84706722/8015; fax: +86 411 84706722.

E-mail addresses: jfzhao@dlut.edu.cn (J. Zhao), Liudi@dlut.edu.cn (D. Liu), yangmj@dlut.edu.cn (M. Yang), songyc@dlut.edu.cn (Y. Song).
[1] Address: School of Energy and Power Engineering, Room 205, Dalian University of Technology, Dalian, Liaoning 116024, PR China. Tel.: +86 41184706722.
[2] Address: School of Energy and Power Engineering, Room 310, Dalian University of Technology, Dalian, Liaoning 116024, PR China. Tel.: +86 41184709093.

reservoirs favor heat transfer. Laboratory-scale hydrate experiments and simulations have been used to accurately predict the behavior of hydrate dissociation in porous media. Yousif et al. [13] conducted experiments on the hydrate formation and dissociation in Berea sandstone cores using depressurization and developed an isothermal model to interpret the results. Masuda et al. [14] developed a two-phase, gas–water, numerical finite-difference simulator to model their experimental depressurization results. Konno et al. [15] studied the dissociation behavior of methane hydrate in sandy porous media below the quadruple point. Sun et al. [16,17] considered the ice-phase to develop a simulator for methane hydrate dissociation in porous media. Rutqvist and Moridis [18] noted that lowering the initial hydrate saturation results in a higher gas production because the effective initial permeability to water is increased.

The heat transfer mode can affect the temperature and pressure distribution and the hydrate permeability in porous media, thereby affecting hydrate dissociation. Experiments and simulations have resulted in researchers exploring the heat transfer mechanisms in hydrate dissociation. Moridis et al. [19] highlighted the thermal conductivity and the specific heat as two important thermal properties. Whereas studies have been conducted to explain heat transfer effects, few studies have focused on the aforementioned thermal properties. Goel et al. [20] modeled gas production from in situ hydrates, considering the sensible heat in the core but neglecting heat conduction and convection effects. Masuda et al. [14] developed a simulator to describe heat transfer by conduction and convection within a sandstone-containing hydrate. Ji et al. [21] studied the decomposition of methane hydrate in a reservoir by depressurization. Heat convection was considered in Smith's model but heat conduction inside and outside the core was neglected, resulting in low gas production. Pooladi-Darvish and Hong [22] compared the importance of convective and conductive heat transfer. Oyama et al. [23,24] use a dissociation model and experimental studies to prove that heat transfer from the surroundings is predominant in the experimental case, and at the low-permeability, the dissociation was driven mainly by sensible heat consumption. Wang et al. [25] find that the heat conduction plays a more significant role than the convection for the heat diffusion in the thermal stimulation process.

An understanding of heat transfer is critical for modeling the hydrate dissociation process. Such insights can explain the effect of heat on hydrate dissociation, including the different conditions and environments around the core. These mechanisms can be used to identify the best exploitation method for natural gas hydrates and the best reactor design for hydrate production.

In this study, our simulator is used to predict the gas production, the pressure, the temperature and the evolution of hydrate saturation during hydrate dissociation. The simulator is used to describe MH dissociation by depressurization in a cylindrical core sample in the radial and axial directions. We focus on the effects of different heat transfer modes in this paper.

2. Mathematical models

Three components (gas, water and hydrate) and three phases (gas, water and solid) are considered in the mathematical model used in this study. The continuity equation, the energy conversion equation, the reaction kinetics equation and the equation of motion are used to model hydrate dissociation in porous media. The equations of state of the three components are also used in this simulation. The assumptions made in the model are given below.

   a. The porous media is homogeneous, and the solid phase (i.e., the hydrate and the porous media) is incompressible and stagnant.

   b. Darcy's law is valid for the water and gas phases. The absolute permeability of the porous media is a function of the hydrate saturation. The relative permeability of the gas and the liquid determine the flow behavior of the two-phase fluid.
   c. The gas does not dissolve in the water.
   d. An ice phase does not form during the entire dissociation process.

2.1. Mass conservation equations

A cylindrical geometry is adopted in the simulation to predict the laboratory-scale behavior of methane hydrate dissociation by depressurization. The gas production, the temperature, the saturation of the three components and the pressure are predicted.

The mass conservation equations for the gas, the water and the hydrate are described by Eqs. (1)–(3):

$$-\frac{1}{r}\frac{\partial}{\partial r}(r\rho_g v_{gr}) - \frac{\partial}{\partial x}(\rho_g v_{gx}) + \dot{q}_g + \dot{m}_g = \frac{\partial}{\partial t}(\phi\rho_g S_g) \tag{1}$$

$$-\frac{1}{r}\frac{\partial}{\partial r}(r\rho_w v_{wr}) - \frac{\partial}{\partial x}(\rho_w v_{wx}) + \dot{q}_w + \dot{m}_w = \frac{\partial}{\partial t}(\phi\rho_w S_w) \tag{2}$$

$$\dot{m}_h = \frac{\partial}{\partial t}(\phi\rho_h S_h) \tag{3}$$

where r denotes the radial distance; ρ_g, ρ_w and ρ_h denote the densities of the gas, water and hydrate, respectively; v_{gr} and v_{gx} denote the radial and the axial velocities of the gas; v_{wr} and v_{wx} denote the radial and axial velocities of water; S_g, S_w and S_h denote the saturation of the gas, water and hydrate; and ϕ denotes the porosity. The total change in the gas mass consists of the change in the gas mass across the boundary, the change in the gas mass for hydrate formation or dissociation, the change in the gas mass in the radial direction and the change in the gas mass in the axial direction. The total change in the water mass is analogous to that of the gas mass. The total change in the hydrate mass is denoted by m_h.

Eq. (4) describes the three-phase saturation:

$$S_g + S_w + S_h = 1 \tag{4}$$

Darcy's law is valid for the water and gas phases. The gas and water velocities can be described using Darcy's law as follows:

$$v_i = -\frac{Kk_{ri}}{\mu_i}\nabla P_i \quad (i = g, w) \tag{5}$$

where P_i is the pressure of the phase i, μ_i is the viscosity of the phase i, and k_{ri} is the relative permeability of the phase i, which can be expressed using Corey's model as follows:

$$k_{rw} = \left(\frac{\frac{S_w}{S_w+S_g} - S_{wr}}{1 - S_{wr} - S_{gr}}\right)^{n_w} \tag{6}$$

$$k_{rg} = \left(\frac{\frac{S_g}{S_w+S_g} - S_{gr}}{1 - S_{wr} - S_{gr}}\right)^{n_g} \tag{7}$$

where S_{wr} and S_{gr} are the water and gas residual saturation, respectively, and n_w and n_g are empirical constants. In this simulation, n_w is 4 and n_g is 2. In Eq. (6), n_w controls the values of the relative water permeability, while in Eq. (7), n_g controls the values of the relative gas permeability. These constants govern the gas and water velocities and affect the convective heat transfer in methane hydrate dissociation.

In Eq. (5), K denotes the absolute permeability of the porous media in the presence of hydrate and is given by Eq. (8), where n denotes the permeability reduction index.

$$K = K_0(1 - S_h)^n \tag{8}$$