



Technical Note

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



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ABSTRACT

Natural gas hydrate dissociation requires the continuous absorption of heat energy from the periphery, which influences both the gas generation rate and cumulative gas production. To predict the potential impact of heat transfer on the hydrate dissociation process, we previously developed and verified a two-dimensional axisymmetric model. In this study, we build on our previous work to investigate the influence of heat transfer on methane gas production by thermal stimulation. The results show that during hydrate decomposition, increasing the specific heat capacity of porous media containing hydrate inhibits the gas generation rate. However, the effects of the initial water content on the gas generation rate and cumulative gas production are weak. The influence of water and methane convection heat on hydrate dissociation is also weak. Increasing thermal conductivity can initially negatively influence hydrate dissociation, but later promote the process.

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1. Introduction

Natural gas hydrate dissociation requires the continuous absorption of heat energy from the periphery, which influences both the gas generation rate and cumulative gas production. To predict the potential impact of heat transfer on the hydrate dissociation process, we previously developed and verified a two-dimensional axisymmetric model [1]. Currently, more than three mining methods, such as depressurization [2–5], thermal stimulation [6–8], and the combined method [9,10], are used for methane gas exploitation [11]. In this study, we expand on our previous work by focusing on the influence of the heat transfer on gas production by thermal stimulation.

In past studies of thermal stimulation, both numerical simulations and experiments have been performed. However, present research mainly focuses on the corresponding kinetic parameters, hydrate saturation and porosity of hydrate sediments, research that analyzes the heat transfer effects are less reported. Wang et al. [6] used the cubic hydrate simulator to study gas production in methane-hydrate-bearing sediments by thermal stimulation. They conclude that the effects of heat conduction are more significant than those of heat diffusion, and furthermore, increasing the hot water injection rate promotes hydrate dissociation, although this has little impact on the final gas generation. Selim and Sloan

[7] presented an analytical model that predicts hydrate dissociation via thermal stimulation. Their results show that the decomposition rate closely related to the thermal properties and porosity of the porous media. Moridis et al. [8] tested methane hydrate dissociation by means of thermal stimulation in order to simulate kinetic hydrate decomposition in porous media.

Heat transfer is an important property used to model the hydrate decomposition process [12]. On the basis of the previous study, sensible heat, conductive heat flow and convective heat transfer are all considered into the analysis of heat transfer effects on gas production by thermal stimulation in this study.

2. Modeling methodology

The mathematical models used in this study, along with the assumptions made by these models, follow on from our previous work, in which they are described in detail [1] and validated [13–15]. The model was utilized to predict the influence of several parameters, including initial water saturation, out pressure, surrounding temperature, absolute permeability, and water phase [13], on hydrate decomposition in the laboratory [14,15]. The model contains three components (gas, water, and hydrate) and three phases (gas, water, and solid). Mass conservation equations, energy conversion equations, reaction kinetics equations, the equation of motion, and the equations of state of the three components are utilized to simulate hydrate decomposition in porous

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media. The modeled core is immersed in a water bath, and the outlet valve is defined to the left-hand side of the core. All of the walls and the right-hand side of the core are considered to be no-slip boundaries (Fig. 1). Free convection heat transfer is assumed between the circumferential wall and the surroundings. At the ends of the core, adiabatic boundary conditions are imposed. These conditions are based on the initial conditions of Masuda et al. [16] and are described as follows:

$$T = T_0 \quad P = P_0 \quad S_h = S_{h0} \quad S_w = S_{w0} \quad S_g = S_{g0} \quad (0 \leq r \leq R, 0 \leq x \leq L).$$

The following boundary conditions are imposed:

$$P = P_0 \quad (x = 0) \quad \partial P / \partial x = 0 \quad (x = L) \quad \partial P / \partial r = 0 \quad (r = 0, R_0) \\ \partial T / \partial r = 0 \quad (r = 0) \quad \partial T / \partial x = 0 \quad (x = 0, L).$$

In the simulations the specific heat capacity of the core material (C_{ps}) is varied, with values of 0, 0.8, and 1.6 kJ/(kg K) applied. These values reflect the specific heat capacity of typical soils (e.g., sand and sandy clay), which range from 0.83 to 1.38 kJ/(kg K). For the analysis of conductive heat transfer effects, the thermal conductivity of the core material (k_s) varies between 1.5 W/(m K) and 8 W/(m K), values that approximate the thermal conductivities of vitreous silica and quartz [17], respectively. The relative permeability is regarded as a measure of the convection heat transfer, with n_w and n_g controlling the values of the water relative permeability, and the gas relative permeability, expressed as $k_{rw} = \left(\frac{S_w - S_{wr}}{1 - S_{wr} - S_{gr}} \right)^{n_w}$ and $k_{rg} = \left(\frac{S_g - S_{gr}}{1 - S_{wr} - S_{gr}} \right)^{n_g}$ respectively. For the basic case, $n_w = 4$ and $n_g = 2$, for low relative gas permeability $n_w = 4$ and $n_g = 4$, and for high relative water permeability $n_w = 2$ and $n_g = 2$.

3. Results and discussion

3.1. Sensible heat effects in the sediment

The sediment material and the water content are the two main factors impacting on sensible heat during hydrate decomposition. Simulation results show that rapid hydrate dissociation occurs in the first 5 min, after which the gas generation rates decrease until the end of the simulation (Fig. 2(a)). Due to the heat from the cap- and base- sediments, cumulative gas production values are similar for all three cases; therefore, the differences in C_{ps} have little influence on cumulative gas production. In contrast, gas production rates clearly respond to changing C_{ps} ; a low C_{ps} results in rapid gas production in the initial dissociation stage (first 3 min), which continues for some time before decreasing rapidly. Conversely, the high C_{ps} simulation takes longer to reach the maximum gas generation rate, at which it remains for only a short period of time before rapidly decreasing.

During methane hydrate dissociation by thermal stimulation, heat is supported by heat flow from the outside. As a result, a

higher C_{ps} requires more heat to increase the sediment temperature, but less heat for hydrate dissociation. In contrast, a lower C_{ps} requires less heat to increase the sediment temperature, but contributes more heat to the sediment for hydrate dissociation. A deep dissociation front is shown in the simulated core temperature distributions at 3 min for different C_{ps} (Fig. 3) consistent with trends seen in the gas generation rate (Fig. 2(a)). The low temperature zone for the higher C_{ps} is much larger than in the other cases. As the three cases have the same initial temperature, the C_{ps} determines the sensible heat in the sediment. Although high C_{ps} contributes to higher initial sensible heat, it requires the input of more heat from outside to increase the core temperature. The simulated core temperature distributions at 3 min (Fig. 3) suggest that higher sediment C_{ps} consumes more heat in order to generate temperature increases, thereby restraining dissociation.

The small variations of cumulative gas production in the three cases suggest that the effects of water content are subtle (Fig. 2(b)). However, a number of observations are still possible. During the initial period of dissociation (<5 min), low S_w make the dissociation faster than the other two cases, while the gas generation rate with low S_w is the first to reach the maximum. This suggests that lower initial water saturation conditions require less heat to increase the temperature of the water, while more heat from the periphery provides for hydrate decomposition; therefore, hydrate with lower initial water saturation values to decompose more rapidly. However, the effects of the initial water content on the gas generation rate and cumulative gas production are weak. In contrast to the effects of sensible heat on hydrate dissociation by depressurization in Ref. [1], the specific heat capacity of the sediment material has a more restrained influence on the gas generation rate by thermal stimulation. And although the higher initial water content inhibits gas generation rate, the inhibiting effects of initial free water content on exploitation are weak.

3.2. Conductive heat flow effects in the sediment

With regard to the predicted gas generation rate and cumulative gas production for different k_s (Fig. 2(c)), the hydrate dissociation is shown to occur during the first 35 min. The gas production rates rapidly reaches a maximum, but then decrease until the end of the process. During the initial stages of gas production, the highest gas generation rate is observed for lowest k_s simulation. However, reactions with higher k_s go to completion more rapidly. The effects of the different k_s on the gas generation rate by thermal stimulation are similar to that by depressurization [1], that is, a high thermal conductivity can have a partially inhibitory effect and does not always promote dissociation, especially beyond the initial stages of the process. In terms of the cumulative gas production, during the first 15 min of simulations cumulative gas production is higher for lower k_s values; however, the curves of the higher and lower k_s simulations intersect at 17 min. From this

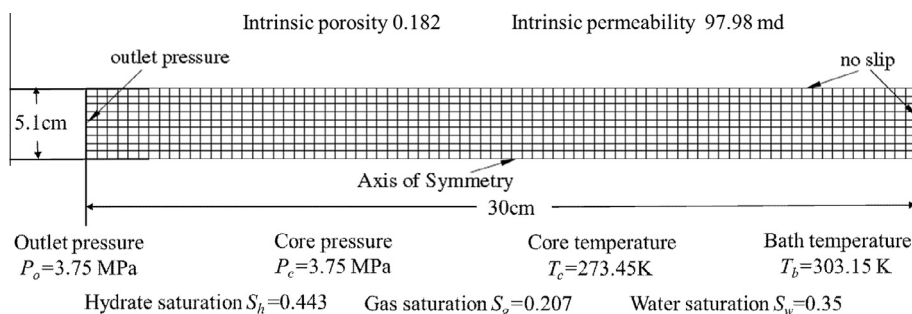


Fig. 1. Schematic of the computational hydrate core sample, as adapted from previous works [1,13–15].

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