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Analyzing the process of gas production for natural gas hydrate using depressurization

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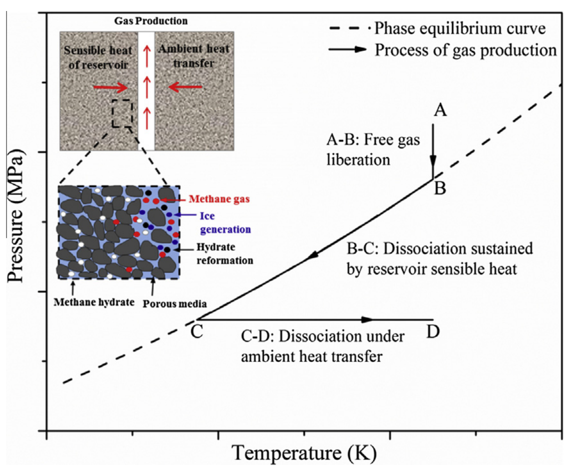
HIGHLIGHTS

- Hydrate dissociation behavior was analyzed in porous media by depressurization.
- The gas production process can be divided into three main stages.
- Methane hydrate first dissociates simultaneously throughout the hydrate zone, and then from the outside.
- The sensible heat of the reservoir and ambient heat transfer play a dominant role in hydrate dissociation.

GRAPHICAL ABSTRACT

Schematic diagram illustrating the process of gas production in hydrate-bearing sediment induced by depressurization. When depressurization occurs, the reservoir pressure and temperature change along the trajectory of A–B–C–D. Character of gas production process is outlined.



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ABSTRACT

Natural gas hydrate is a vast energy resource with global distribution in permafrost regions and in the oceans; its sheer volume demands that it be evaluated as a potential energy source. Understanding the mechanisms of natural gas extraction from hydrate-bearing sediments is critical for the utilization of hydrate accumulations. In this work, methane hydrate dissociation was performed in three kinds of porous media at production pressures of 2.2 MPa, 2.6 MPa, and 3.0 MPa. Results show that the methane gas production process can be divided into three main stages: free gas liberation, hydrate dissociation sustained by the sensible heat of the reservoir, and hydrate dissociation driven by ambient heat transfer. In the process of gas production, hydrate dissociation occurs simultaneously throughout the hydrate zone along the phase equilibrium curve, and then spreads radially from the outside as a result of ambient heat transfer. Hydrate reformation and ice generation always occur in the reservoir interior due to insufficient heat transfer. The use of porous media with increased thermal conductivity accelerates the gas production rate; however, it has little influence on the final percentage of gas production. Furthermore, the Stefan (Ste) number and dissociation rate constant were employed to evaluate the impact of the sensible

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heat of the reservoir and ambient heat transfer. Results indicate that the sensible heat of the reservoir and ambient heat transfer play a dominant role in hydrate dissociation, and that both are dependent on production pressures.

1. Introduction

Natural gas hydrate is a solid, non-stoichiometric crystalline compound in which gas molecules are trapped within a lattice of ice-like crystal structure [1]. It mainly occurs in two distinct geographic settings: in the permafrost and beneath the sea floor under high-pressure and low-temperature conditions [2,3]. Despite the uncertainty inherent in such estimates, it is believed that natural gas hydrate formations contain between $2.0 \times 10^{14}\,m^3$ and $1.2 \times 10^{17}\,m^3$ of methane (STP) [4], a comparatively large amount relative to the $1.5 \times 10^{14}\,m^3$ of methane estimated to exist in conventional gas reserves [5]. Although natural gas hydrate contains tremendous energy reserves, extraction has proven extremely challenging and has yet to be fully realized [6].

There exist three basic techniques to extract gas contained within natural gas hydrate sediment [7]. The first, known as depressurization, involves reducing the reservoir pressure below the range in which the natural gas hydrate is stable. The second, thermal stimulation, requires increasing the reservoir temperature above the natural gas hydrate equilibrium temperature for prevailing pressure. Finally, the third, chemical inhibitor stimulation, calls for the addition of strong hydrogen-bonding chemicals (such as methanol or glycol), leading to a shift in natural gas hydrate equilibrium. Considering the feasibility of exploiting different reservoirs and the economic problems encountered in natural gas production [8,9], depressurization is believed to be the most effective of the three methods and can be used either alone or in combination with the other two techniques [10,11].

To determine changes occurring in the process of natural gas production and induced by the depressurization method, Holder and Angert [12] first reported depressurization-induced gas production from a natural gas hydrate reservoir underlain by a free gas layer, and pointed out that the thermal capacity of the reservoir was sufficient to provide the energy necessary for hydrate dissociation. Meanwhile, Yousif et al. [13,14] investigated natural gas production and the hydrate dissociation front in Berea Sandstone cores, and constructed a three-phase model to explain the dissociation process in detail. Based on their results, they concluded that depressurization was likely the mechanism driving hydrate dissociation in porous media. Kono et al. [15] found that the kinetic dissociation rate could be adjusted by controlling sediment properties in the measurement of natural gas hydrate dissociation using the depressurization method. Moridis et al. [16–18] emphasized that the relative permeability in hydrate-bearing deposits was a complex process which played a critical role in depressurization-induced gas production from Class 1 and Class 2 hydrate deposits. Additionally, Ji et al. [19] conducted a parametric study of natural gas production from hydrate dissociation in a confined reservoir and found the rate of gas production to be a function of well pressure, reservoir temperature, and zone permeability; these results were consistent with those obtained by Nazridoust [20]. Linga et al. [21] investigated the recovery of methane from a variable-volume bed of hydrate by depressurization. The results showed that the rate of recovery was initially dependent on the bed size, and then the dependency became weaker until the rate was constant. Lee et al. [22] analyzed the recovery of natural gas from hydrate-bearing porous rock using depressurization. In comparing the rates of gas production and propagation of the dissociation front, they confirmed that the degree of depressurization, which represented the difference between reservoir pressure and gas production pressure, significantly influenced the rate of gas production. The character of depressurization-induced gas production from oceanic hydrate-bearing sediments was investigated by Moridis and Sloan [23] and Konno et al. [24], using the simulation method. Both concluded that the success of gas production was strongly dependent on the effective permeability and initial temperature of sediments. However, little work has analyzed the effects of natural gas hydrate reformation and ice generation on gas production, phenomena that are commonly observed when employing depressurization [25,26].

Natural gas hydrate dissociation is a complex process that occurs during heat and mass transfer with the dissociation kinetics of hydrate [27]. To investigate the performance of gas production from hydrate-bearing layers underlain by a free gas zone, Hong and Pooladi-Darvish [28] constructed a 2D cylindrical simulator that considered fluid flow, conductive and convective heat transfer, and the intrinsic kinetics of hydrate dissociation. Li et al. [29] investigated the kinetic behaviors of hydrate dissociation in porous media via the depressurization method. Their results suggested that hydrate dissociation rate decreased with time due to a decline in heat transfer efficiency from the boundary to the inner deposit. In addition to this research on natural gas hydrate dissociation, current studies are also taking into account the effects of heat transfer on hydrate dissociation. Pooladi-Darvish and Hong [27] developed a model to study the effects of conductive and convective heat flow on gas production from natural gas hydrate by depressurization. They further studied the heat supplied from the base- and cap-rock and the sensible heat within the hydrate, and determined that this heat had a far greater effect on gas production than that supplied by convection. Additionally, Oyama et al. [30,31] compared natural gas hydrate dissociation characteristics in artificial sedimentary cores and low-permeability hydrate-bearing cores during the depressurization process. They developed a hydrate dissociation model taking into account heat and mass transfer. Recently, Song et al. [32] constructed a two-dimensional axisymmetric simulator to investigate the effects of heat transfer on natural gas hydrate dissociation using the depressurization method. The results indicated that water content and the thermal properties of porous media were two factors that significantly affected gas production. Meanwhile, Li et al. [33] performed experiments in a novel pilot-scale hydrate simulator and pointed out the methane gas production was controlled by the rates of pressure reduction and heat transfer in the hydrate-bearing sediment. While the heat transfer characteristics of hydrate-bearing sediment (representing heat conduction, heat convection, and sensible heat) are key factors influencing hydrate dissociation [30,32,34], few studies have focused on the effects of sediment thermal properties on the hydrate dissociation process. The thermal properties, which denote the parameters of thermal conductivity, specific heat, and thermal diffusivity, play an important role in assessing gas production from hydrate-bearing sediments, heat transfer during hydrate dissociation, and hydrate plug dissociation in oil and gas pipelines [35]. It is therefore essential to clarify how the thermal properties of porous media affect the hydrate dissociation process induced by depressurization.