



Heat transfer analysis of methane hydrate dissociation by depressurization and thermal stimulation

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ABSTRACT

The dissociation of natural gas hydrate is an endothermic reaction closely related with the heat transfer characteristics in porous media. This study mainly focuses on the three-dimensional heat transfer behaviors during hydrate dissociation by depressurization and thermal stimulation based on the experiments in a Cuboid Pressure Vessel (CPV). The evolution of various heat flows (including the heat transferred from the boundaries Q_B , the injected heat from the well Q_{inj} , the heat consumed by the hydrate dissociation Q_H , and the sensible heat change of the deposit Q_S) and their relationships during hydrate dissociation are obtained through numerical simulation. The heat loss Q_L during gas production is calculated and analyzed for the first time. It is found that the hydrate dissociation is mainly promoted by the driving forces of depressurization (F_{dep}) and thermal stimulation (F_{ths}), which are dependent on the heat flows of Q_B and Q_{inj} , respectively. The effect of F_{dep} will be weakened under higher F_{ths} . Part of Q_{inj} and Q_B are absorbed and stored as Q_S by the porous media and the fluids of the deposit. Once Q_B becomes negative, it starts to make contribution to the heat loss instead of the hydrate dissociation, resulting in a sharp increase of Q_L . In addition, a proper thermal stimulation rate q and production pressure P_W should be selected so that the hydrate dissociation rate could be significantly enhanced while the thermal efficiency and energy efficiency are still favorable when compared with using single depressurization.

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1. Introduction

Natural gas hydrates (NGHs) are crystalline solid compounds usually formed by water and small gas molecules under low temperature and high pressure conditions, and they mainly exist in two different geologic environments: in the permafrost and in deep ocean sediments, where the required thermodynamic conditions occur for their formation and stability [1]. The amount of CH_4 trapped in naturally occurred hydrates is estimated to be so large (between 10^{15} and 10^{18} ST m^3 [1]) that the energy production from NGHs shows a great potential for the ever-increasing global energy demand [2]. Based on the fact that the hydrate formation properties are relevant to the gas species and the formation conditions [3], people have proposed various kinds of hydrate-based industrial applications, such as energy storage [4] and gas separation [5–7]. In addition, the occurrence of gas hydrate in pipelines has also raised a lot of safety concerns in the oil and gas industry [8,9].

With the purpose of natural gas hydrate exploitation as an energy source, several kinds of dissociation methods have been proposed and tested from laboratory to field-scale evaluations in recent years, such as depressurization [10–14], thermal stimulation [15–18], thermodynamic inhibitor injection [19–21], and CO_2 replacement method [22–24]. All the methods are based on the destruction of gas hydrate stability conditions, and sufficient heat is required for the endothermic reaction of hydrate dissociation. The depressurization method is generally thought to be the first choice for hydrate exploitation because of its technical simplicity and economic effectiveness, and it has been successfully carried out for the field-scale hydrate exploitation tests in the eastern Nankai Trough, Japan [25] and in the Shenhu Area, South China Sea [26]. However, the gas production rate always drops to an undesirable level in a short period due to the limited sensible heat of the hydrate deposit and the low heat transfer rate from the surroundings [27]. Comparatively, the hydrate dissociation rate of depressurizing can be obviously raised by providing additional heat using thermal stimulation method, which enhances the gas recovery efficiency to a favorable level [2].

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Nomenclature

c_p	specific heat (kJ/(kg·K))	ΔH	dissociation heat of methane hydrate (kJ/kg)
F_{dep}	driving force of depressurization (kJ)	Δt	duration of heat injection (min)
F_{ths}	driving force of thermal stimulation (kJ)	Δx	discretization along the x -axis (m)
K	intrinsic permeability (m ²)	Δy	discretization along the y -axis (m)
$k_{\theta C}$	thermal conductivity (W/(m K))	Δz	discretization along the z -axis (m)
$k_{\theta RD}$	thermal conductivity of dry porous medium (W/(m K))	ρ	density (kg/L)
$k_{\theta RW}$	thermal conductivity of fully saturated porous medium (W/(m K))	χ	thermal efficiency
$k_{\theta I}$	thermal conductivity of ice (W/(m K))	η	energy efficiency
m_H	mass of dissociated hydrate (kg)	ϕ	porosity
P	pressure (MPa)	λ	van Genuchten exponent – Table 2
P_{eq}	equilibrium pressure (MPa)		
q	thermal stimulation rate (W)	<i>Subscripts and Superscripts</i>	
q_B	heat flow rate across the boundaries (W)	0	denotes initial state of production
Q_B	cumulative heat across the boundaries (kJ)	A	aqueous phase
Q_H	cumulative heat consumed by hydrate dissociation (kJ)	B	boundary
Q_{inj}	cumulative heat injected (kJ)	cap	capillary
Q_L	cumulative heat loss (kJ)	G	gas phase
Q_S	sensible heat change of the deposit (kJ)	H	solid hydrate phase
S	phase saturation	irA	irreducible aqueous phase
t	time (min)	irG	irreducible gas
T	temperature (°C)	n	permeability reduction exponent – Table 2
V_p	cumulative volume of the produced CH ₄ (L)	n_G	gas permeability reduction exponent – Table 2
x, y, z	Cartesian coordinates (m)	W	well

No matter which method is chosen for hydrate dissociation, one of the most important factors that determine the gas production efficiency is the heat transfer process in the entire hydrate reservoir [2]. It is thus critical to obtain sufficient knowledge of the heat transfer mechanisms and the affecting factors for the design and optimization of gas production method. Zhao et al. [11] performed the hydrate decomposition experiments in three kinds of porous media by depressurization. The results showed that the hydrate dissociation was promoted by the sensible heat of the deposit and the ambient heat transfer. Oyama et al. [28] proved that the heat transferred from the environments was dominant for the depressurization-induced hydrate dissociation. Wang et al. [29] compared the hydrate dissociation behaviors above and below the ice point by depressurization. The latent heat released by ice formation was confirmed to be able to increase the gas production rate significantly. Fitzgerald et al. [16] observed short periods of heat transfer limited regimes in two of the four thermal stimulation based hydrate dissociation experiments. The free water production was found to play a role in increasing the convective heat transfer. Based on the core-scale experimental data and numerical simulation results, Chen et al. [30] found that the core-scale hydrate dissociation is more heat-transfer controlled. An increase in the deposit or boundary temperature will make the production more efficient due to the higher latent heat and faster heat transfer rate during the dissociation process. A general conclusion from these studies is that the hydrate dissociation is affected by different kinds of heat flows in the hydrate deposit. However, the quantitative relationships of these heat flows are not discussed in the above studies.

Different production methods will result in different heat transfer modes, thus leading to different hydrate dissociation efficiency. Song et al. [31] evaluated the production performance of methane hydrates using depressurization, thermal stimulation and combined methods. It was found that the combined method had obvious advantages for hydrate exploitation over the depressurization and warm-water-injection method. Falser et al. [32] investigated the production performance of methane hydrate by combining

depressurization with simultaneous heating of the wellbore. They concluded that a lower heating temperature at the wellbore was sufficient to enhance the hydrate dissociation, and the available sensible heat of the formation would be exhausted quickly when the wellbore was only depressurized and not heated. Li et al. [33] conducted several methane hydrate dissociation experiments under depressurization and electrical heating in a Cuboid Pressure Vessel (CPV). It was found that the injected heat could be transferred efficiently from the well to the hydrate deposit and thus enhanced the gas recovery rate obviously. The above studies all indicate that the depressurization combined with thermal stimulation method is a better choice for hydrate exploitation. However, they lack a comprehensive and quantitative analysis of the dependence of hydrate dissociation on the heat transfer processes. It is still not clear how the depressurization and thermal stimulation affect each other, and thus enhance the hydrate dissociation efficiency.

As another alternative and effective method for the study of heat transfer during hydrate dissociation, numerical simulation has got remarkable development in recent years. It can help us understand and predict hydrate dissociation behaviors under different heat transfer modes by yielding results based on detailed knowledge at the present state of the art. Moridis et al. [27] conducted the simulation of the gas production potential of the hydrate deposits on North Slope, Alaska using the TOUGH+HYDRATE (T+H) code developed from the TOUGH2 family codes at the Lawrence Berkeley National Laboratory [34]. The results indicated that the initial deposit temperature was an important factor controlling production performance as it determined the sensible heat available for hydrate dissociation. Liu et al. [35,36] established a one-dimensional model which could describe the convective-conductive heat transfer and mass transfer behaviors in the gas and hydrate zones separated by a moving front. The movement of this front was found to be strongly dependent on the convective and conductive heat flows from the reservoir. Zhao et al. [18] developed a two-dimensional axisymmetric model and investigated the effect of heat transfer on methane gas production

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