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Influence of intrinsic permeability of reservoir rocks on gas recovery from hydrate deposits via a combined depressurization and thermal stimulation approach

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HIGHLIGHTS

- The gas recovery efficiency from hydrate deposits can be effectively promoted through thermal stimulation.
- Increasing reservoir permeability weakens the enhancement effect of thermal stimulation.
- Characteristic shifting from radial to uniform hydrate dissociation is promoted by increased permeability.

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ABSTRACT

Reservoir permeability is a crucial controlling factor for the successful exploitation of unconventional gas hydrate resources, which represent a vast natural gas reserve with substantial energy potential. Numerical simulations and analyses are essential tools for the prediction and evaluation of natural gas recovery from hydrate deposits. In this study, a two-dimensional axisymmetric model was developed and validated to investigate the effect of the intrinsic permeability of reservoir rocks on hydrate dissociation characteristics induced by a combined depressurization and thermal stimulation method. Simulation results indicate that the average gas production rate from hydrate deposits could be enhanced when thermal stimulation was additionally applied at the same production pressure, but the enhancement effect weakens as reservoir permeability increases. Pressure reduction propagates slowly from gas production wells into cores with low-permeability, and thermal stimulation dominates hydrate dissociation. However, depressurization can play a determining role for hydrate dissociation in high-permeability cores which benefit to the propagation of pressure reduction. Increased permeability promotes the characteristic shift from thermal-stimulation-governed radial hydrate dissociation to depressurization-determined uniform dissociation. To a certain extent, increased permeability enhances gas generation, but there is a threshold beyond which this effect is no longer felt as excessive consumption of sensible heat restricts further hydrate dissociation. Although there are many uncertainties in the hydrate dissociation process in porous media, numerical simulation can provide useful information for evaluating the feasibility of methodology for gas recovery from gas hydrate reservoirs.

1. Introduction

Natural gas hydrates, which form hydrogen bonding enclosures of vast natural gas stores, have been recognized as future fossil fuel resources with great potentialities [1,2]. Natural gas hydrates are generally abundant in permafrost and in deep-sea sediments, where low ambient temperatures and high pore pressures naturally coexist [3]. The amount of organic carbon preserved in gas hydrate reservoirs is conservatively estimated to be approximately twice the total carbon amount in all other fossil fuels (coal, oil, and natural gas) on Earth [4]. The occurrence of phase conversion, including hydrate dissociation/reformation and ice generation, as well as sediments deformation when

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Nomenclature

A	heat transfer area (m^2)
A_s	reaction ratio surface area (m^2)
C_p	specific heat (J/(kg·K))
h	enthalpy of phase (J/kg)
K	absolute permeability (mD)
K_0	intrinsic permeability (mD)
k	relative permeability of gas or water
k_d	intrinsic reaction constant (mol/(m^2·Pa·s))
M	molecular weight
$\dot{m}$	mass of phase for hydrate dissociation (kg/(s·m^3))
N	permeability reduction factor, $N = 15$
N_h	hydrate number, $N_h = 5.75$
n_c	empirical constants in Eq. (25), $n_c = 0.65$
n_w	empirical constants in Eq. (7), $n_w = 4$
n_g	empirical constants in Eq. (8), $n_g = 2$
P	pressure (Pa)
P_c	capillary pressure (Pa)
P_c^e	entry pressure in Eq. (25), $P_c^e = 1$ kPa
P_e	equilibrium pressure (Pa)
P_0	initial pressure (Pa)
$\dot{q}$	energy source (J)
r	radial distance (m)
R	universal gas constant (kJ/(kg·K))
S	saturation of phase
S_{gr}	gas residual saturation
S_{wr}	water residual saturation
T	temperature (K)
t	time (s)
v	velocity of fluid phase (m/s)
x	axis distance (m)

Symbols

φ	porosity
μ	viscosity (Pa·s)
λ	conductivity coefficient (w/(m·K))
ρ	density of phase (kg/m^3)
σ	gas throttle coefficient (J/(kg·Pa))
α	heat transfer coefficient (W/(m^2·K))

Subscripts

c	core
g	gas phase
w	water phase
h	hydrate phase
s	sediment phase
in	heat transfer from surrounding ambient

producing hydrate resources make it much unique compared with utilizing the conventional fossil fuel [5]. Research on natural gas recovery from hydrate reservoirs has greatly progressed over the last few decades; however, the extreme challenge of extracting these fuels still remains [6]. Several recovery methods including depressurization, thermal stimulation, and inhibitor injection have been proposed for utilizing the hydrate resources [7–9]. Depressurization has been recognized as the most effective method for natural gas recovery from gas hydrates, taking into consideration both production costs and engineering feasibility [10–12]. Gas production rate can also be effectively enhanced by the thermal stimulation method [13]. However, it should be noted that each of these methods, when employed independently, has its own unavoidable disadvantages, including the relatively low gas recovery efficiency of depressurization [14], high energy loss of thermal stimulation [15], and high cost of inhibitor injection [16].

To enhance gas production efficiency and overcome the limitation of any single method, the combined approach has been developed [17]. Depressurization, which serves as the basis of the combined methodology, has been extensively used to induce gas production from hydrate deposits either alone or in combination with other techniques [18,19]. Several thermal stimulation methods, including thermal huff and puff [20], warm water/brine injection [21], water/air bath immersion [22], and microwave heating [23], have been employed to enhance the effectiveness of gas production in laboratory scale studies. Song et al. [24,25] experimentally determined that the combined method has an obvious advantage in the energy efficiency comparing with single warm water injection and can effectively suppress ice generation and hydrate reformation occurring during single depressurization induced gas production process. Wang et al. [26,27] claimed that depressurization assisted thermal stimulation is the optimum method for the hydrate dissociation in the water-saturated sample by analyzing the fluid flow mechanisms and the heat transfer characteristics during the gas recovery from hydrate reservoirs. Falser et al. [28] experimentally demonstrated that gas production increased by 3.6 times on average by using the combined additional wellbore heating approach relative to the depressurization-only method. Liang et al. [29] employed electrical heating to enhance gas production efficiency, but suggested that heating should be terminated when net energy begins to decrease. Minagawa et al. [30] further found that electrical heating can be an effective method for enhancing gas recovery efficiency from depressurized hydrate deposits under low temperature or low thermal conductivity conditions. To date, most studies have indicated that a combined approach is more advantageous for hydrate exploitation than any single production method [17]. These studies have primarily focused on gas production rates, energy efficiency, and method optimization; however, few studies analyzed how the intrinsic property of reservoir rocks may affect gas recovery behavior.

Gas production from hydrate deposits is generally based on a hydrate dissociation process which involving phase conversion, gas-water multiple flow, and heat transfer [31]. Reservoir permeability, which governs the gas-water flow in hydrate deposits as well as influences the heat transfer and hydrate dissociation, is a crucial factor for controlling the hydrate dissociation behavior in porous media and therefore decides the economic and continuous development of hydrate resources [32,33]. Oyama et al. [34] experimentally found that depressurization induced hydrate dissociation behavior in a natural core with low permeability was different from that in a high-permeability artificial core, and claimed that the pressure propagated slowly and hydrate dissociation mainly driven by sensible heat consumption. Given the fact that a strong correlation between the gas production rate and gas recovery efficiency and the permeability of hydrate deposits has been demonstrated by Hong et al. [35]. The effective permeability of sediments containing gas hydrates largely depends on the pore structure of the host sediments, hydrate saturation, and hydrate occurrence within pore spaces [36,37]. Several analytical models containing multiple fitting parameters have been proposed to describe the permeability of reservoir containing gas hydrate [38–40]. However, it is still incredibly difficult to clarify the effective permeability evolution during hydrate dissociation due to experimental challenges [33]. Among all, the maximum effective permeability of hydrate deposits was limited by the intrinsic permeability of reservoir rocks in the absence of gas hydrates [41,42]. Here, we assume that simulated reservoir rocks are homogeneous, and that the gas/water/hydrate phases are uniformly distributed within the pore space. The effective permeability of hydrate