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Review

# Evaluation of gas production from methane hydrates using depressurization, thermal stimulation and combined methods

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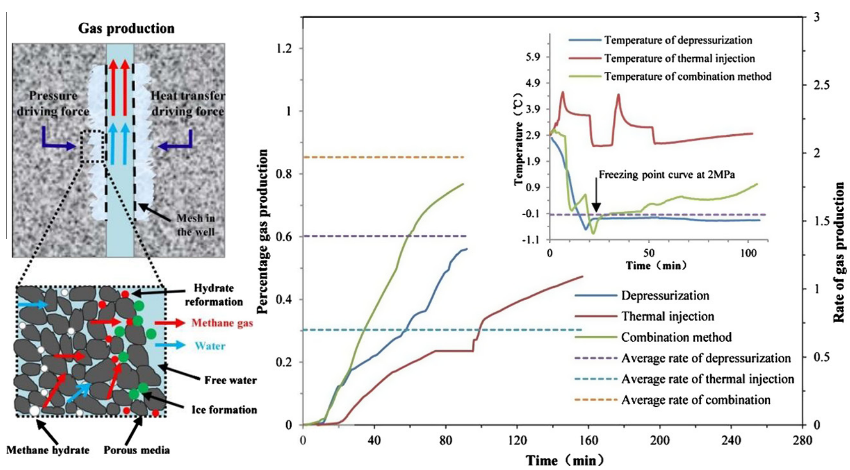
## HIGHLIGHTS

- Three gas production methods were evaluated with different hydrate saturations.
- The roles of temperature, pressure, sensible heat and heat transfer were analyzed.
- The driving force of hydrate dissociation at different stages was analyzed.
- The combined method effectively improved the gas production and energy efficiency.

## GRAPHICAL ABSTRACT

The schematic diagram of hydrate decomposition process and the gas production by using different methods.

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## ABSTRACT

To investigate the gas production from methane hydrate-bearing sediments, the gas production processes from methane hydrate in porous media using depressurization, two-cycle warm-water injection and a combination of the two methods were characterized in this study. The methane hydrates were formed in porous media with various initial hydrate saturation ($S_{hi}$) in a pressure vessel. The percentage of gas production, rate of gas production, and energy efficiency were obtained and compared using the three methods. The driving force of the hydrate dissociation at different stages of depressurization was analyzed and ice formation during the gas production was observed. For the two-cycle warm-water-injection method, the percentage of gas production and the energy efficiency increased with increasing of $S_{hi}$. However, due to the large amount of warm water needed to heat the porous media at the dissociation site, the percentage of gas production was lower than the other two methods under the same experimental conditions. The experimental results proved that the combined method had obvious advantages for hydrate exploitation over the depressurization and warm-water-injection method in terms of the energy efficiency, percentage of gas production and average rate of gas production, and with increasing of $S_{hi}$, the advantages are enhanced. For the $S_{hi}$ of 51.61%, the percentage of gas production reaches 74.87%, which had increments of 18.63% and 31.19% compared with the depressurization and warm-water-injection

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methods. The energy efficiency for the combined method were 31.47, 49.93 and 68.13 for $S_{hi}$ of 31.90%, 41.31% and 51.61%, respectively.



**Contents**



## 1. Introduction

Gas hydrates are known to occur worldwide in locations such as the permafrost regions and beneath the sea [1,2]. They have important impacts on flow assurance, safety issues, energy recovery, transportation and climate change [3,4]. Due to this potential resource, the gas production technologies of natural gas from gas hydrate have become of great interest. Currently, various methods of gas production from hydrate reservoirs have been proposed, and most methods are based on breaking the phase equilibrium of gas hydrate, mainly through depressurization method, thermal stimulation method, inhibitor injection method, carbon dioxide replacement method, etc. [5–7]. The obvious gas production approaches involve depressurization, heating and combined methods [8]. The approaches and production methodologies that have been investigated cover a wide range of alternatives. However, there are some salient limitations in the state of knowledge [9–11].

It has been found that the least energy-intensive method suggested is the depressurization technique, where the heat of decomposition is provided by the surrounding formation [12]. Field tests at Mackenzie Delta, North Slope, Alaska and Nankai Trough along the Pacific coast of Japan also revealed that depressurization is a promising gas production method from the perspectives of energy efficiency and productivity [13–16]. At 2013, Japan Oil, Gas and Metals National Corporation conducted a flow test from March 12 until March 18 in the first offshore production test off the coasts of the Atsumi and Shima peninsulas using a depressurization method, which had a gas production duration of 6 days and an average gas production volume of 20,000 $m^3$/day [17]. In Canada, Aurora Mallik, a similar field test performed for onshore production was also conducted using a depressurization method in 2007–2008 [18]. However, some key problems are still not clear. The depletion of sensible heat, the low rate of gas production, the formation of ice and the blocking effect are the key problems, which should be further researched to improve the gas recovery efficiency. More details of the depressurization method have being studied in the laboratory. Yousif et al. used a three-phase 1D model implemented using experimental results to describe the dissociation process of methane hydrate in Berea sandstone via depressurization. They predicted the volume of gas and dissociation front location and proved that the resistance of gas production increased during the dissociation process [19]. Sun et al. [20] measured the kinetic data for methane hydrate dissociation at various temperatures and pressures in a sapphire cell apparatus via the depressurizing method. They concluded that when the system temperature was lower than 0 °C the hydrate dissociation was controlled by gas diffusion because of the formation of ice, and the hydrate dissociation process was then treated as a moving boundary problem. Konno et al. use a large reservoir simulator, the High-pressure Giant Unit for Methane-hydrate Analyses to simulate field-like gas production behavior through laboratory experiments. They proved that more in-place methane could be produced when the production pressure was decreased to 2.1 MPa, which is below the quadruple point [21]. For the decomposition of hydrate using the depressurization process, the gas production rate is obviously restricted when there is no heat input due to the strong endothermic effect and small natural heat flux of the hydrate sediments [22]. The sensible heat is insufficient for dissociating all the existing methane hydrate. After exhausting the sensible heat, the gas production rate turns downward because of the lack of hydrate dissociation heat. The gas production rate at this stage stabilizes at a very low level, which would not be economically viable [21]. In addition, the formation of ice and the reformation of hydrate during the decomposition process also have an impact on the gas production [23]. Macrocosmic numerical results also show that for depressurization of gas hydrate sediment in the South China Sea, the hydrate deposit exploitation by depressurization only is not a good method because of the secondary hydrate formation and ice formation at the wellhead during the hydrate dissociation [17,24,25]. Therefore, based on depressurization, the application of thermal stimulation in certain stages of depressurization is one of the effective methods worthy of study [8,25,26].

The thermal injection method could effectively improve the problems that emerged in the depressurization process, such as