Applied Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Evaluation of thermal stimulation on gas production from depressurized methane hydrate deposits☆

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HIGHLIGHTS

- Natural gas is recovered from hydrate deposits using combined depressurization-thermal stimulation method.
- Five main stages of gas production upon occurrence of ice generation phenomena.
- Two types of thermal stimulation methods are used.
- The positive effects of thermal stimulation are confirmed.

ARTICLE INFO

Keywords:
Natural gas hydrates
Depressurization
Thermal stimulation
Heat flux
Warm water injection

ABSTRACT

Natural gas hydrates have gained worldwide attention as an important potential non-conventional fossil fuel resource. Understanding the gas production behavior from hydrate deposits is critical to the utilization of the gas hydrate resource. In this study, the hydrate dissociation reaction was induced by depressurization in conjunction with thermal stimulation. Profiles of temperature, pressure, gas production rate, and cumulative gas production during the gas production processes were analyzed. The results show that the gas production process upon ice generation can be divided into five main stages: (1) a free gas release, (2) hydrate dissociation along the equilibrium curve driven by the reservoir sensible heat, (3) hydrate dissociation driven by the exothermic ice generation reaction, (4) ice melting and hydrate dissociation under ambient heat transfer, and (5) hydrate dissociation under ambient heat transfer. During the gas production process, two thermal stimulation methods—ambient heat transfer and warm water injection—were employed to supply heat for hydrate dissociation. The larger the heat flux supplied by ambient heat transfer, the greater the gas production. During the warm water injection process, the gas production time decreased as the temperature of the injected water increased. These two methods can effectively promote gas production from gas hydrate deposits. The findings of this study can provide some insight for designing and implementing optimal production techniques for use of hydrate resources.

1. Introduction

Natural gas hydrates have gained worldwide attention as a potential alternative energy resource [1,2]. A comparatively large volume of natural gas hydrates with high energy density are known to be distributed in permafrost and beneath the sea floor where combinations of high pressures and low temperatures maintain hydrate stability [3,4]. It is estimated that the total carbon content in natural gas hydrates is approximately twice that in other fossil fuels [5]. Although gas hydrate deposits may be significant energy reserves, energy recovery from these reservoir has been proven over the past decades to be extremely challenging [6–9]. Recently, researchers have proposed several methods for extracting the natural gas from hydrate deposits by shifting the local thermodynamic equilibrium. The methods generally include (a) the depressurization method, which requires decreasing the reservoir pressure below the local hydrate stable pressure [10–12], (b) the thermal stimulation method, which raises the reservoir temperature above the local hydrate stable temperature [13,14], (c) the chemical injection method, in which by chemicals are injected into the reservoir to shift the local hydrate stability boundary into the more rigorous conditions (higher pressure of lower temperature) [15], (d) the gas exchange method, in which gases such as CO_2 or a CO_2/N_2 mixture are injected into the hydrate reservoir to replace the methane from hydrate [16].

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http://dx.doi.org/10.1016/j.apenergy.2017.08.005
Received 15 January 2017; Received in revised form 27 July 2017; Accepted 4 August 2017

Please cite this article as: Wang, B., Applied Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.08.005

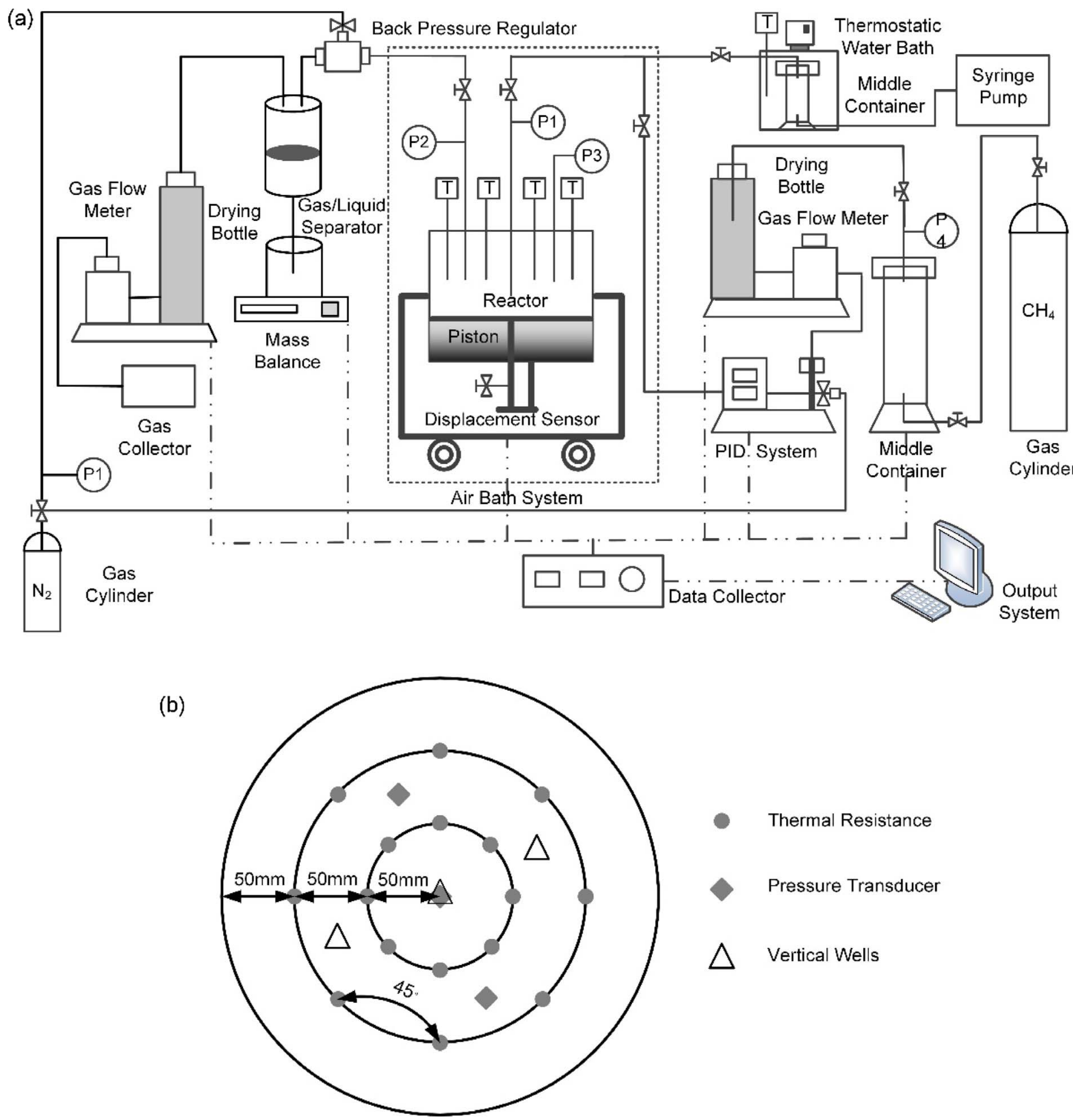

Fig. 1. (a) Schematic diagram of the experimental apparatus; (b) distribution of thermal resistances and pressure transducers on the top cap.

Depressurization has been recognized as the most feasible and economical method for utilizing the gas hydrate resource [17,18]; in a field test at the Mallik site in Canada [19] and an offshore test at the Nankai Trough in Japan [20], depressurization method was used for inducing gas production from hydrate deposits. Li et al. [21,22] experimentally investigated the gas production behavior from methane hydrate sediment using depressurization, and described a three-stage gas production process: free-gas production, mixed-gas (a combination of free gas and dissociated gas from hydrate) production, and single dissociated-gas production. Linga et al. [23] used depressurization to recover natural gas from hydrate-bearing sediment, and shown that a higher bottom hole pressure resulted in slower gas production and that ice generation occurred at a lower bottom pressure, due to insufficient heat supply. Moreover, Oyama et al. [24] clarified that the reservoir sensible heat contribution to hydrate dissociation increases exponentially with the reduction of the pore pressure. Both field and laboratory tests have confirmed that depressurization is an effective gas production method; however, depressurization induced hydrate dissociation is strictly limited by heat transfer [20,25], and blockage problems caused by ice generation and hydrate reformation can occur in a single depressurization induced gas production operation [23,26,27]. Seol and Myshakin [28] visually observed gas hydrate reformation phenomena during depressurization without heat supply from the surroundings. Kuhs et al. [29] also confirmed the local reformation phenomena during depressurization induced xenon-hydrates decomposition operation using a synchrotron X-ray computed tomographic microscopy. Thus, abundant heat supply is a critical factor for efficient gas production from hydrate deposits, because of the endothermic hydrate dissociation reaction [30] and the strong Joule–Thomson cooling effect at the production well [31]. Thermal stimulation can effectively minimize problems such as insufficient heat supply, ice generation, and hydrate reformation during a single depressurization operation [32,33], and combinations of the depressurization method and thermal stimulation method can be employed to elevate the gas production efficiency and overcome the lack of energy during hydrate dissociation [34,35]. Several heat supply modes, such as