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The use of electrical heating for the enhancement of gas recovery from methane hydrate in porous media

Bo Li, Sheng-Dong Liu, Yun-Pei Liang*, Hang Liu

State Key Laboratory of Coal Mine Disaster Dynamics and Control, Chongqing University, Chongqing 400044, China
College of Resources and Environmental Science, Chongqing University, Chongqing 400044, China

HIGHLIGHTS

- Dissociation behaviors of methane hydrate are studied in a Cuboid Pressure Vessel.
- The combination of depressurization and electrical heating is employed and evaluated.
- The use of electrical heating could enhance the gas production significantly.
- The effects of key parameters on gas production are investigated.

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ABSTRACT

The gas production behaviors of methane hydrate dissociation induced by depressurization and electrical heating are investigated in a Cuboid Pressure Vessel (CPV) with an effective volume of 1.5 L. The vertical well located at the axis of the vessel is used as the production well, and a resistance heating wire is distributed uniformly in the inner surface of the well for heat injection. Hydrate samples with the similar phase saturations are prepared and then decomposed under depressurization and electrical heating. A total of five experimental runs have been carried out with different production pressure (3.50, 4.50, and 5.50 MPa) and electrical heating power (0, 25, and 50 W). It is found that methane hydrate can be dissociated continuously in the CPV in each run, which proves the feasibility of the used method for hydrate exploitation in porous media. Compared with the pure depressurization case (run 3), both the gas production and hydrate dissociation rates could be increased to a much higher level when a relatively slow heat injection rate is supplied from the well. In addition, the net energy E_{net} can be recovered with a much faster rate under constant electrical heating rate, and the final amount of E_{net} is only a little lower than that of run 3. They all indicate that the production efficiency of depressurization can be greatly enhanced by employing the electrical heating simultaneously. A maximum E_{net} can be obtained in each case with constant electrical heating, and it is suggested that the production process should be terminated before E_{net} begins to drop. The gas production performance is generally more favorable under lower production pressure and a higher electrical heating rate.

1. Introduction

Natural gas hydrates (NGH), which are ice-like solid compounds containing hydrogen-bonded water molecules and small gas molecules, have been found to be widely and abundantly distributed in the permafrost and the ocean sediments, where the high pressure and low temperature conditions meet the requirements of their stability [1]. The majority of gas trapped in naturally occurred hydrates is methane, and the amount is such large that they have attracted numerous attentions as a kind of new and clean energy to meet the fast increase of the global energy demand [2]. Natural gas hydrates mainly exist with the following three kinds of structures: structure I, II, and H, which are dependent on the gas species and the conditions of formation [3]. Based on the hydrate formation abilities of different gases, people have also proposed various kinds of hydrate-based industrial applications, such as energy storage [1,4] and gas separation [5–7].

Aiming to realize the recovery of natural gas from hydrate deposits, people have proposed a variety of methods for hydrate dissociation. All the methods could be generally divided into the following categories: (1) depressurization [8–12], in which the reservoir pressure is declined below the hydrate equilibrium pressure; (2) thermal stimulation [13–16], in which the reservoir temperature is raised above the

* Corresponding author at: College of Resources and Environmental Science, Chongqing University, Chongqing 400044, China.
E-mail address: liangyunpei@cqu.edu.cn (Y.-P. Liang).

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equilibrium temperature by external heat injection; (3) thermodynamic inhibitor injection [17–19], in which chemicals, such as methanol, alcohol and brine, are used to destroy the current equilibrium conditions of hydrates and make them no longer stable; (4) CO_2 replacement method [20–22], in which liquid CO_2 is applied to replace the methane gas in the lattices because of its more moderate formation conditions. In order to investigate the hydrate dissociation and gas production behaviors using the above methods in the laboratory, a variety of hydrate simulators have been built and developed in recent years. Pang et al. [23] have set up a middle-sized reactor with the volume of 10 L, and the hydrate dissociation under thermal stimulation has been studied. Yang et al. [24] have built a cylindrical reactor of which the inner space is divided into two sections to model the hydrate-cap gas reservoirs in the seafloor. Fitzgerald et al. [15] have constructed a cylindrical pressure vessel (59.3 L) for the investigation of hydrate dissociation via a point source thermal stimulation. Li et al. [25,26] have designed and set up two three-dimensional hydrate simulators with the effective volume of 5.8 L and 117.8 L, and both of them have been used to investigate the production efficiency of depressurization and hot water stimulation. Based on the idea of *in-situ* combustion for the thermal stimulation, Schicks et al. [27] have developed a large laboratory reservoir simulator (LARS) with the inner volume up to 425 L, and the replacement process of CH_4-CO_2 has also been studied. Generally, the laboratory simulators are becoming larger and larger to be able to represent the field-scale hydrate deposit better.

Among the four single methods mentioned above, the depressurization method is the first choice because of its good economic efficiency. However, the gas production rate under depressurization is often too slow to be acceptable because of the limited sensible heat and the low heat transfer rate of the hydrate deposit [28–30]. In addition, hydrate reformation and water freezing under sharp depressurization could be severe, which further results in obvious decrease of the effective permeability and the gas production rate [31]. On the other hand, the thermal stimulation method can provide additional heat and thus obviously enhance the gas production rate, while the energy efficiency shall be very low if it is applied alone [25,32]. Thus, the combination of depressurization and thermal stimulation is generally agreed to be the optimal method for hydrate production because of the dual driving forces [2,33,34]. Wang et al. [35] compared the gas production behaviors using depressurization and the combined methods, and they observed a synergistic effect of depressurization and heat stimulation on hydrate dissociation. Similar results were also obtained by Song et al. [28] and Feng et al. [19,32] when depressurization and warm-water injection were employed for the gas production from methane hydrate-bearing sediments. A general conclusion of all the above studies is that the combination of depressurization and thermal stimulation could lead to higher gas production rate and shorter production time when compared with single depressurization method. However, the energy efficiency remains questionable if the heat is injected in the form of hot water or steam, as the heat loss would be considerable during the hot fluid delivery through hundreds of meters from the surface of the ground/ocean to the hydrate deposit [2,15,27].

Therefore, other alternative methods of thermal stimulation should be introduced to overcome these drawbacks. Based on the above conventional methods, the application of electrical heating in certain stages of depressurization is attracting the attention of some researchers. Compared with the conventional hot fluids injection modes (e.g., water or steam), the use of electrical heating is one of the typical *in-situ* thermal stimulation methods which can obviously enhance the heat utilization efficiency. As the heat source is placed directly inside the hydrate deposit, heat losses caused by the down-hole fluid transportation could be eliminated [2]. Callarotti [36] modeled the production process of the submarine methane hydrate deposits at the depths of 1000–1500 m by electrical heating, and the energy return on energy invested (EROI) was analyzed. The simulation results showed that the EROI values were located in the range of 4–5, which indicated favorable energy efficiency of this kind of thermal stimulation method. Minagawa et al. [37] set up an electrical heating apparatus and examined the efficiency of electrical heating for hydrate dissociation. Due to the consideration of safety, xenon gas was used as the hydrate-forming gas instead of methane. Two end caps acted as a pair of electrodes and alternating current was supplied to them to heat the hydrate sediment. The results showed that the electrical heating of the hydrate layer combined with depressurization was an effective method for gas production from hydrate dissociation. Falser et al. [31] devised an apparatus and 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 gas production rate was increased by 3.6 times as compared with pure depressurization experiment. Li et al. [38,39] numerically evaluated the gas production potential of the DK-2 gas hydrate deposit in the Qilian Mountain permafrost by means of *in-situ* heat injection method. Relatively stable gas production and hydrate dissociation rates could be obtained under the conditions of continuous depressurization and pure heat injection in the horizontal wells. Generally, the electrical heating has been proved to be theoretically feasible for hydrate dissociation, while little experimental evaluation and verification of its operational possibility and commercial feasibility can be found in the literature. The key factors which can determine the final production efficiency of the electrical heating method are still not clear. This kind of method is to be of great use especially for some tight deposits where it is hard to apply conventional thermal stimulation methods (hot water or steam injection) to produce gas from hydrate dissociation [2].

Thus, this study aims to further investigate and evaluate the production efficiency of electrical heating on hydrate dissociation. We have developed an experimental apparatus equipped with resistance heating system in the vertical production well located at the axis of the vessel, and methane hydrate samples are dissociated safely under different electrical heating power and production pressure. The gas production rate, the hydrate dissociation rate, and the net energy efficiency using this kind of method are analyzed in detail for the first time, and they are all compared with pure depressurization method to demonstrate its commercial feasibility. In addition, the dependence of the gas production performance on the depressurization driving force during constant electrical heating process is also investigated.

2. Experiment

2.1. Apparatus

Fig. 1 shows the schematic of the experimental system for the methane hydrate formation and dissociation. The core of this system is a Cuboid Pressure Vessel (CPV), a high-pressure reactor that is made of stainless steel. The inner effective volume of the CPV is 1.5 L with the length, width and height of 100, 100 and 150 mm, respectively. In order to obtain a low-temperature environment, the whole reactor is immersed in a water bath which can maintain a stable operation temperature from −5 to 30 °C with precision of ± 0.1 °C. The evolutions of temperature inside the vessel are measured by the 9 thermocouples shown in Fig. 2. They are all placed in the middle layer of the CPV in a square area of 80 × 80 mm, with the distance of two adjacent thermometers being 40 mm. The thermometer at the axis is T5, which is connected closely to the outside surface of the well, and those in the corners are T1, T3, T7 and T9, respectively. An electrical power device is used to supply 0–180 V direct current (DC) for the electrical resistance to generate heat inside the vessel.

The methane gas needed for hydrate formation is supplied by a gas tank (2 L, 0–25 MPa) through a PID controller (Tescom, 0–6000 psi, ± 0.1%) located at the inlet of the reactor. To measure the system pressure, there are two pressure transducers connected to the pipelines of the top and the bottom of the CPV, respectively. A back-