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Experimental investigation into gas production from methane hydrate in sediment by depressurization in a novel pilot-scale hydrate simulator

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ABSTRACT

The gas production behavior from methane hydrate in the sediment by depressurization was investigated in a novel pilot-scale hydrate simulator (PHS), a three-dimensional pressure vessel of 117.8 L. Experimental results are compared with those in a cubic hydrate simulator (CHS) with the effective volume of 5.8 L to reveal the dependence of the production behavior on the size of the hydrate reservoir. Results show that the gas production processes in the two simulators consist of three periods: the free gas production, mixed gas (free gas and gas dissociated from the hydrate) production and gas production from hydrate dissociation. The first and second periods are mainly controlled by the pressure reduction rate. The heat conduction from the ambient is main driving force to dissociate the hydrate in the third period. The cumulative gas production in the third period with the PHS and CHS is much higher than those in the first and second periods. However, the gas production rate in the period is low. The duration for gas production with the PHS is approximately 20 times as many as that with the CHS. Water production behavior with the PHS is different with that with the CHS during the gas production. The system temperature change tendency with the PHS is the same with that with the CHS during the gas production. The unique difference is that there is also a temperature rise period with the CHS.

1. Introduction

Fossil fuels currently provide about 85% of the world's commercial energy needs [1]. On a relative basis, natural gas (NG) is the fastest growing energy source in the world [2]. Gas hydrates are ice-like inclusion compounds formed from water and gas molecules at high pressures and low temperatures. Over the last decade, there has been a dramatic increase in gas hydrate research, such as natural gas production, carbon dioxide sequestration and separation [3,4]. 1 m^3 of methane hydrate will release approximately 170 m^3 of methane gas at standard temperature and pressure. Natural gas hydrate (NGH) is being recognized as a potential strategic energy resource [5], it is because NGH is vastly distributed throughout both the marine and permafrost areas [6,7]. A variety of methods have been proposed to exploit this energy resource: (a) thermal stimulation; (b) depressurization; (c) injection of inhibitors [8]. Depressurization is a gas recovery method to dissociate methane hydrate (MH) through altering the pressure value in the reservoir to a point below the equilibrium value corresponding to the reservoir temperature [9]. Depressurization method is used most commonly because of its highest energy profit ratio. Unlike the thermal stimulation or the inhibitor injection method, the depressurization method does not require any additional costs. Thus, it has been applied for gas production from the Messoyakha hydrate gas reservoir in Russia [10]. Earlier studies indicated that the depressurization method is the most promising dissociation method in the majority of hydrate deposits because of its simplicity, its technical and economic effectiveness, the fast response of hydrates to the rapidly propagating pressure wave, the near-incompressibility of water, and the large heat capacity of water [11–13].

Recently, a variety of the mathematic and experimental investigations into the hydrate production behaviors by depressurization have been undertaken. Sun et al. [14] developed a one-dimensional numerical model to simulate two regimes of gas production from the sediments containing methane hydrates by depressurization. Song and Liang [15] developed a two-dimensional axisymmetric simulator for gas production from hydrate reservoirs and simulated the process of laboratory-scale hydrate decomposition by

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depressurization and found the high surrounding temperature and low outlet valve pressure may increase the rate of hydrate dissociation. Tang et al. [16] carried out the experimental work on the methane gas production from an experimental-scale hydrate reservoir by depressurization and used the hydrate reservoir simulator, Tough-Fx/Hydrate, to simulate the gas production behavior. The results suggested that the hydrate dissociation kinetics has a great effect on the gas production behavior for the laboratory-scale hydrate-bearing core. However for a field-scale hydrate reservoir, the flow ability dominates the gas production behavior and the effect of hydrate dissociation kinetics on the gas production behavior can be neglected. Oyama et al. [17] used an artificial sedimentary core and performed several depressurization experiments under various production pressure conditions and developed a numerical model for methane hydrate dissociation process in the porous media to analyze the physical phenomena in a methane hydrate reservoir. Lee et al. [18] designed and set up an experimental apparatus to analyze the dissociating phenomena of the hydrate in the porous rock. Depressurization experiments were carried to investigate into the dissociation characteristics and the productivity of the dissociated gas. The results verify that the degree of depressurization is a significant factor influencing the gas production rate in a hydrate reservoir. Haligave et al. [19] reported the recovery of methane from a variable-volume bed of silica sand and hydrate by depressurization. They found that the gas production consists of the two periods. The rate of gas recovery is strongly dependent on the silica sand bed size during the first stage, and depends weakly on the size during the second stage. Sakamoto et al. [20] conducted the experimental studies on the dissociation of methane hydrate and gas production behaviors by depressurization in the sediments. They investigated into the horizontal radial flows in the porous media during methane hydrate dissociation under a variety of vertical loads in order to reproduce field conditions in the real methane hydrate sediments. It was found that the methane hydrate dissociation consisted of two stages due to the latent heat of sediments and thermal conduction. Kono et al. [21] measured the dissociation rates of methane gas hydrate in various custom-designed porous sediments by the depressurizing method, and derived the kinetic dissociation rate equation. They reported that the dissociation rate can be adjusted by controlling the sediment properties. So far, the experimental studies on methane dissociation and gas production by depressurization are carried out using the small one-dimensional or two-dimensional experimental apparatuses [14–21].

Because there are some differences of the control mechanisms for gas hydrate production with the lab-scale hydrate reservoir and the field-scale hydrate reservoir [16], it is difficult to test the validity of numerical simulation schemes for hydrate dissociation using the experimental data with a small one-dimensional or two-dimensional experimental apparatus. Thus, it is significant to investigate into the potential influence of the size of the experimental reservoir on the production behavior of the hydrate by depressurization. On the other hand, the real hydrate reservoir is a three dimensional (3D) reservoir. In order to investigate into the gas production characteristics in a 3D reservoir, it is very significant to simulate the hydrate dissociation behaviors in the 3-D experimental apparatus. Recently, we have reported the investigation into the gas production behavior from methane hydrate in the porous sediment by depressurization in a three-dimensional cubic hydrate simulator (CHS) with the effective volume of 5.8 L [22]. The results show that the gas production process consists of three periods: the free gas production, mixed gas (free gas and gas dissociated from the hydrate) production and gas production from the hydrate dissociation. The temperature changes in the near-well region and the far-from-well region in the 3D hydrate reservoir during gas production contain the five stages and four stages, respectively. In the gas production process, the resistances in the hydrate reservoir change with the hydrate dissociation and the gas and water flows. The gas hydrate dissociation in the gas production process is mainly controlled by the rate of the pressure reduction in the system and the heat supplied from the ambient. The water production has been almost completed in the free gas production process.

In this work, the pilot-scale hydrate simulator (PHS), a novel three-dimensional 117.8-L pressure vessel, has been developed for the investigation into the gas production behavior of the methane hydrate in the sediment by using depressurization method. The experiments were performed at the hydrate saturation of 30% and environmental temperature of 281.15 K. These conditions simulate the ones of the hydrate reservoir in the Shenhu Area, South China Sea. The gas production pressure is 4.7 MPa. In addition, the investigation into the potential dependence of the production behavior on the size of the hydrate reservoir was carried out by comparison with the results obtained from using a three-dimensional medium-size cubic hydrate simulator (CHS) with the effective volume of 5.8 L [22].

2. Experimental section

2.1. Experimental apparatus

The schematic of the experimental apparatus used in this work is shown in Fig. 1. The PHS, a novel 117.8-L pressure vessel, is made of stainless steel. The PHS can withstand pressures of up to 30 MPa. The low temperatures required for the experiments are obtained by placing the whole apparatus encircling a water jacket (−15–30 °C, ±0.1 °C) inside the walk-in cold room (−8 °C–30 °C, ±2 °C). Fig. 2 shows the schematic of the layers and the well design of the PHS. As shown in Figs. 1 and 2, there are three horizontal layers named Layers A–A, B–B and C–C inside the vessel, which equally divide the vessel into four regions. The distance between Layer A–A and Layer B–B is 150 mm, a quarter of the internal length of the PHS, which is the same with that between Layer B–B and Layer C–C, while Layer B–B is in the middle of the PHS. As shown in Fig. 2, a 9-spot distribution of the vertical wells is fixed in the top flange (the Top Surface) of the PHS, and there are three vertical wells at each spot (V1, V2, . . . , V9), which extend into the vessel to Layers A–A, B–B, and C–C, respectively. As a typical example, it is shown in Fig. 2 that Wells V5A, V5B and V5C are all placed on Spot V5, and the bottoms of these wells are on Layers A–A, B–B and C–C, respectively. Wells V5A, V5B and V5C are at the axis of the PHS. In general, a total of 27 vertical wells are distributed in the PHS, and the wells on Spots V1, V3, V7 and V9 are all immediately close to the inside edge of the PHS, and the bottom of each well is right on the corresponding layer.

As shown in Fig. 2, in the Right Surface of the PHS, 3 horizontal wells, Wells HA, HB and HC, are inserted into Spots H1, H2 and H3 on Layers A–A, B–B and C–C, respectively. Each horizontal well is extended to the inside surface of the Left Surface of the PHS. Fig. 3 shows the schematic of the distribution of the thermometers (the temperature measuring spots) in the PHS. There are 49 thermometers evenly distributed on each layer, with a total of 147 spots in the PHS. In other words, on each layer (Layers A–A, B–B and C–C), it is a 49-spot distribution of the thermometers (T1–T49), with T25 at the center and T1, T7, T43, and T49 at the corner. The thermometers at the same spots are distinguished by the different layers, for example, as shown in Fig. 3, the 43th thermometer on Layer A–A is called T43A, and those on Layer B–B and Layer C–C are T43B and T43C, respectively. The distribution of the resistance ports is the same with that of the thermometers, with the corresponding name of R1–R49. As shown in Fig. 3, the 43th