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Effect of horizontal and vertical well patterns on methane hydrate dissociation behaviors in pilot-scale hydrate simulator

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HIGHLIGHTS

- Effect of vertical and horizontal wells on hydrate dissociation behaviors are compared.
- Depressurization and thermal huff and puff are employed for hydrate dissociation.
- Hydrate dissociation, heat transfer, energy ratio, and thermal efficiency are compared.

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ABSTRACT

Exploitation of natural gas hydrate is expecting to be an important strategic way to solve the problem of energy depletion. Understanding the effectiveness of the well configuration plays a pivotal role in gas production from the hydrate reservoir. This study evaluates the methane hydrate dissociation behaviors using both vertical well and horizontal well experimentally. Methane hydrate in porous media has been synthesized in a 117.8 L pilot-scale hydrate simulator (PHS), which is equipped with 9 (3 × 3) vertical wells and 9 (3 × 3) horizontal wells. The condition of hydrate formation is corresponding to the ocean depth of 1200 m and it is similar to the hydrate characteristics of the South China Sea. Hydrate is dissociated under depressurization and thermal stimulation. The results indicate that, for the depressurization and thermal stimulation methods, the gas production rate, the heat transfer rate, and the accumulative dissociation ratio with the horizontal well pattern are higher than those with the vertical well pattern. Meanwhile, the evaluations of the energy ratio and the thermal efficiency indicate that the horizontal well pattern has the advantage of higher production efficiency by the thermal stimulation. Thus, it is determined that the production performance is better using the horizontal well pattern.

1. Introduction

Natural gas hydrates are crystalline solid compounds which are formed at high pressures and low temperatures in the permafrost region and subsea floor [1]. Although it is uncertain, the common estimation of the global methane hydrate is as large as 2×10^{16} m^3 on the continental margins [2,3]. Gas hydrate has been considered as a potential strategic energy on account of the abundant carbon gas trapped in this resource [4]. At present, common methods proposed for hydrate dissociation are depressurization [5–9], thermal stimulation [10–12], inhibitor stimulation [13–15], carbon dioxide replacement [16,17], and the combined utilization of these methods [18].

In addition to the dissociation methods, the gas production is highly influenced by the well patterns, because the heat-transfer and the fluid flow in the hydrate reservoir are controlled by the well configuration. The configuration of well pattern not only should be according to the intrinsic character of the hydrate reservoir, but also is restricted to the practical geological conditions. Some researchers have investigated this issue by the numerical simulations. For example, Moridis et al. [19] indicated that horizontal well was impractical at the UBGH2-6 site of the Ulleung basin in the Korean East Sea due to the layered stratigraphy and the presence of mud layers. Their investigation indicated that production from such a hydrate accumulation with the vertical well was feasible. While in the Qilian Mountain permafrost, the numerical simulation of Zhao et al. [20] showed that the single vertical

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well by depressurization was not promising, and they suggested that other methods such as a single horizontal well design may be more economical for gas production at the Qilian Mountain permafrost. Li et al. [21] investigated the gas production performance by the huff and puff method with a single horizontal well in the Shenhu Area, and the results showed that the gas production rate was lower than the acceptable standard of commercial gas production. The similar result was carried out by Su et al. [22] when the numerical simulation was conducted by the huff and puff method with a single vertical well. Furthermore, Feng et al. [23] reported that in the South China Sea, the dual horizontal wells placed in the same horizontal plane has the advantage of higher productivity than that placed in the same vertical plane.

Not only the numerical simulation, but also the field test and the laboratory test are essential to investigate the feasible exploitation technology of methane hydrate. So far, because the field test is costly and time-consuming, only Japan has carried out the field test of marine hydrate exploitation in the Nankai Trough in May 2013 [24]. Consequently, the laboratory test acts as a significant role in the study of gas production technology. Recently, the different sizes of the large-scale reactors have been built to simulate the formation and dissociation processes of the hydrate. A 72.2 L seafloor process simulator [25] has been manufactured at the Oak Ridge National Laboratory, USA. This reactor has been applied for the investigation into the hydrate formation and dissociation under the condition of marine water depth of 2 km. Later on, a 72 L reactor was fabricated by Zhou et al. [26] to investigate the methane gas production behaviors from methane hydrate by depressurization. Fitzgerald et al. [27] have investigated the net energy efficiency of gas production by in-situ heating in a 70 L reactor. The results showed that the net energy efficiency of 72% were achieved during 10 h test period with the heating at 100 W. In addition, within the framework of the German national research project, a 425 L large laboratory reservoir simulator (LARS) was set up by Schicks et al. [28] to study the thermal stimulation by using in situ combustion. They also investigated the CH_4–CO_2 swapping process in this simulator. Moreover, a High-pressure Giant Unit for Methane-hydrate Analyses (HiGUMA) was developed by Kono et al. [29] to study the gas recovery factor of methane hydrate by different schemes of depressurization in sandy sediment. The internal volume of the HiGUMA is 1710 L, furnished with a single vertical system. These large-scale hydrate simulators have made great contributions to studying the formation and dissociation conditions of the hydrate as well as the feasible exploitation technology for the future.

However, all of the above-mentioned hydrate simulators were only equipped with a single production well. It was hard to investigate the different well patterns on gas production from hydrate bearing sediment by using these simulators. Li et al. [30] built a 117.8 L cylindrical hydrate simulator, which was equipped with 9 (3×3) vertical wells and 9 (3×3) horizontal wells, making it the unique hydrate simulator associated with multi-well configurations. This pilot-scale hydrate simulator (PHS) consists 147 ($7 \times 7 \times 3$) temperature measuring points, making it possible to precisely predict the thermal front in the process of hydrate formation and dissociation. In recent years, they had assessed the production performance of methane hydrate in the sandy reservoir through a single vertical well by the depressurization and the huff and puff method [31]. They also introduced the SAGD method from oil industry into hydrate decomposition with the PHS, in which the dual horizontal wells were applied [32].

Up to now, little attention has been paid to the studies of the different well configurations in the laboratory tests. Few references reported about the comparison of the effects of the vertical well and the horizontal well on the hydrate dissociation behaviors in the porous media sediment by numerical or experimental simulation.

In this work, the investigation into the effects of the vertical and horizontal well patterns on gas production behaviors has been carried out in a pilot-scale hydrate simulator. The central vertical well and the central horizontal well are selected as the production well. In the practical field, the horizontal well can be much longer than the vertical well because most of the distributions of the hydrate reservoirs are horizontal layered. To compare the effect of the same well section, the vertical and horizontal wells are of the same length in this study. Meanwhile, the depressurization and the thermal stimulation are employed to dissociate the hydrate. The cumulative gas production, the accumulative dissociation ratio, the energy ratio and the thermal efficiency are selected as the indicators to evaluate the production performance.

2. Experimental section

2.1. Experimental apparatus

The detailed information of the PHS has been reported in the previous studies [6,31]. Fig. 1 shows a schematic drawing of the apparatus. A cylindrical pilot-scale hydrate simulator (PHS) fabricated from 316 stainless is the core of the apparatus. The maximum working pressure of the PHS is 30 MPa. The inner effective volume of the PHS is 117.8 L with the height of 600 mm, and the diameter of 500 mm. To avoid the non-uniform effects of boundary temperature, the PHS is placed in a cold room (−8–30 °C, ±30 °C) and it is surrounded by a water jacket (−15–30 °C, ±0.1 °C) to maintain the temperature stable. To measure the pressure of the system, an inlet and an outlet pressure transducer are placed in the top and bottom of the PHS, respectively. The production pressure at the well is adjusted by a back-pressure regulator situated in the outlet (from the Nantong FeiYu Company, 0–30 MPa, ±0.2 MPa). A metering pump (from Beijing ChuangXinTongHeng Company, 0–250 mL/min, ±0.1 mL/min) is acted as the injection equipment, and a heater (from the Nantong FeiYu Company, 0–6 kw, ±0.1 kw) is used to provide the hot water or steam. A gas/liquid separation equipment is placed in the outlet to separate the produced fluid. Two gas flow meters (from the Seven Star Company, 0–100 L/min, ±2%) are applied to measure the injected gas and produced gas, respectively. The quantity of the water production is measured by a balance (from the Guangzhou ZhiCheng Electronic Scale Company, 0–30 kg, ±1 g). All of the parametric variations during the experiment are collected by the data acquisition system.

Fig. 2 gives the schematic of the inner PHS and the well configurations in this work. The inner PHS is divided into four regions of the same size by three horizontal layers, which are named as Layers A–C, respectively. The central vertical well is situated along the axis of the PHS. The central horizontal well is placed in the middle of the Layer B. Both the gas production by the depressurization and the thermal stimulation are conducted with the central vertical well and the central horizontal well, respectively.

Fig. 3 shows the schematic of the distribution of the thermal couples in the PHS. As seen in Fig. 3, there are 49 ($7 \times 7 = 49$) thermal couples on each layer. Therefore, the total amount of the thermal couples in the PHS is 149 ($49 \times 7 = 147$). The name of the thermal couples in the PHS can be explained as follows: as an example, the 43rd thermal couples situated on Layers A–C are named as T43A, T43B, and T43C, respectively.

2.2. Experimental procedure

2.2.1. Hydrate formation

Table 1 lists the formation and dissociation conditions for the experiments. The detailed information of the hydrate formation process has been introduced by Wang et al. [33]. Firstly, quartz