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Production behaviors and heat transfer characteristics of methane hydrate dissociation by depressurization in conjunction with warm water stimulation with dual horizontal wells

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ABSTRACT

To investigate into the synergistic effect of depressurization and heat stimulation on hydrate dissociation and the three-dimensional heat transfer characteristics during hydrate dissociation in the porous media, a series of the hydrate dissociation experimental runs by the depressurization in conjunction with warm water injection with DWDH (dual horizontal wells) and single depressurization have been carried out in a three-dimensional CHS (cubic hydrate simulator). The results indicate that the gas production process can be divided into the free gas release stage, the mixed gas release stage, and the dissociated gas release stage. In the first two stages, the gas production is mainly controlled by the depressurizing rate. In the third stage, the duration of the hydrate dissociation with the DWDH method (water injection temperature equals to environmental temperature) is much shorter than that by the single depressurization. It is due to the fact that water injection enhances the heat convection and further increases the rate of the hydrate dissociation. The analysis of three-dimensional heat transfer shows that the heat transfer rate along the injection well is the fastest. Energy analysis indicates that the sensible heat of the hydrate reservoir is insufficient for the hydrate dissociation, and the heat for the hydrate dissociation mainly originates from the boundaries.

1. Introduction

Natural gas hydrate is ice-like solid, which is constituted of gas molecules (mostly methane) and water molecules. The gas molecules are trapped in water cavities that are composed of hydrogen-bonded water molecules. Gas hydrate has been discovered in the subsurfaces in permafrost regions and oceanic sediments [1]. Current estimate of the amount of methane in the natural gas hydrate reservoirs is approximately 20,000 trillion m^3. There is a growing consensus that gas hydrate can be a potential future energy resource because of the abundant natural gas trapped in this resource. Therefore, it becomes a research focus to find the effective technologies for extracting gas from natural gas hydrate economically [2].

Till now, the methods proposed for the hydrate dissociation include the depressurization [3–5], the thermal stimulation [6–11], the chemical injection [12,13], and the CO_2 replacement [14–17]. Because of the advantages of low cost and easy operation, the depressurization is considered as a feasible method for the hydrate dissociation. Recently, the researches on the hydrate dissociation by depressurization have been carried out by the experiments and numerical simulations [18–20]. The experimental observations of Li et al. [18] demonstrated that the gas production in the earlier stage of depressurization was mainly controlled by the rate of the pressure reduction. Ruan et al. [19] further found that more gas can be extracted by lowering the depressurizing rate in a certain depressurizing range with the numerical simulation. The experimental investigation of Li et al. [20] indicated that the hydrate dissociation rate was limited in the later stage by depressurization when the sensible heat of the hydrate reservoir was insufficient. Thus, other methods should be combined with depressurization to enhance the recovery efficiency in the later stage of the hydrate dissociation process.

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Thermal stimulation can break the equilibrium state of the hydrate and cause the hydrate dissociation. In most of the researches [6–8] on the thermal stimulation, the steam injection, hot water (>50 °C) injection, or electromagnetic heating is used for the hydrate dissociation. Moridis et al. [21] reported that pure thermal injection for the hydrate dissociation was not economic because most of the injected heat was absorbed by water and the porous media. Feng et al. [22] conducted a numerical simulation of the hydrate dissociation under the combination of the depressurization and warm brine (<30 °C) stimulation with the dual horizontal wells. Their results indicated that the warm brine injection (28 °C) had the higher energy efficiency than the hot brine (90 °C) injection.

Depressurization and the thermal stimulation have their individual advantages and disadvantages. Some researchers tried to adopt the joint method for the hydrate dissociation. Li et al. [23] evaluated the efficiencies of the different methods by the experimental investigation. The results indicated that the combination of the depressurization and thermal stimulation was more feasible for the hydrate dissociation. Nonetheless, the previous work was mainly focused on the conjunction of the depressurization and thermal stimulation. Little attention has been paid to the analysis about which of them is the main factor for the hydrate dissociation.

It is important to study the heat transfer characteristics during the gas production from the hydrate reservoir because the hydrate dissociation is an endothermic reaction [24]. In 1989, Selim and Sloan [25] presented a physical model to describe hydrate dissociation under the thermal stimulation in porous media. Hydrate dissociation was considered as a moving boundary process in their model. In 1997, Makogon used the classical Stefan's model for melting to describe the process of hydrate dissociation. Heat transfers by conduction and convection were considered in his model [26]. Recently, some experimental studies on the heat transfer characteristics during the hydrate dissociation were presented. Katsuki et al. [27] studied the heat and mass transfer during the dissociation of methane hydrate in the sediment made of glass. Zhao et al. [28] analyzed the heat transfer of methane hydrate dissociation in a cylindrical reactor. The results showed that heat was mainly transferred by conduction from the dissociated zone to the dissociating zone. However, practical hydrate reservoirs are three-dimensional, and little references were reported about three-dimensional heat transfer in the process of the hydrate dissociation in the porous media so far.

In this work, the depressurization in conjunction with warm water injection with DWDH (dual horizontal wells) was employed to investigate into the production behaviors and heat transfer characteristics in a CHS (cubic hydrate simulator). On account of the low density of methane gas and the effects of gravity on water, the lower horizontal well was set as the injection well, and the produced fluids were extracted from the upper one. To reduce energy loss, warm water (<30 °C) instead of hot water (>50 °C) was injected into the hydrate reservoir for hydrate dissociation in this work. Evaluations of the effects of the depressurizing rate and the injection temperature on the hydrate dissociation were carried out. In addition, the heat transfer characteristics along the three coordinate axes were also analyzed.

2. Experiments

2.1. Experimental apparatus

Fig. 1 shows the schematic of the experimental apparatus in this study. The details of the apparatus have been reported in our previous work [6,9,18,23]. This apparatus mainly consists of a reaction system, an injection system, a gas recovery system, and a data acquisition system. The core of the reaction system is a cubic hydrate simulator (CHS), which is made of stainless steel 316. The CHS with the maximum working pressure of 25 MPa is immersed in a thermostat to keep the temperature steady. The inner edge of the CHS is 180 mm, and the effective volume is 5.832 L. The inner schematic and the distribution of thermal couples in the CHS are displayed in Fig. 2. This cubic reactor is equally divided into four regions by three layers, which are named as Layer A, Layer B, and Layer C, respectively. The upper horizontal well (Well HA) and the lower horizontal well (Well HC) are located in Layer A and Layer C, respectively. There are 5 thermal couples evenly distributed along both the *x*-axis and *y*-axis on each layer. A total of 125 ($5 \times 5 \times 3 = 125$) thermal couples are installed in the CHS. The distance between the adjacent thermal couples along every coordinate axis is 45 mm. As shown in Fig. 2, each thermal couple can be

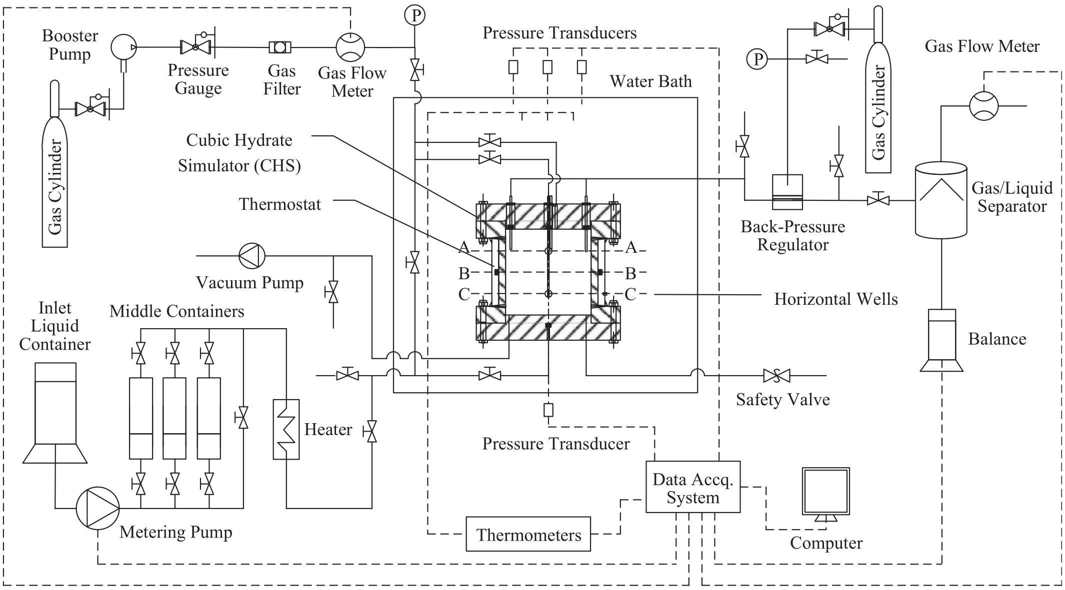

Fig. 1. Schematic of the experimental apparatus.