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Three dimensional experimental and numerical investigations into hydrate dissociation in sandy reservoir with dual horizontal wells

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ABSTRACT

In this study, both three dimensional experimental and numerical investigations of hydrate dissociation have been carried out by depressurization in conjunction with warm water stimulation using dual horizontal wells. Hydrate has been synthesized in the porous sediment in a CHS (Cubic Hydrate Simulator). The results of gas and water production, hydrate dissociation, and temperature distribution by numerical simulation are in good agreement with the experimental results. The results show that hydrate dissociation evolves by means of ablation with double-moving boundary. One dissociation interface moves from the injection well to the neighboring regions, and the other dissociation interface spreads from the boundary to the central reservoir. The assessment of the energy ratio shows that the depressurization in conjunction with warm water stimulation using dual horizontal wells is a promising method for hydrate dissociation. Sensitivity analyses show that raising the injection temperature causes a sharply decline of energy ratio, although it increases the gas production rate at a certain time. Additionally, reducing the intrinsic permeability of the reservoir can decrease the energy ratio and increase the time for the completion of hydrate dissociation.

1. Introduction

Natural gas hydrates are ice-like compounds in which the molecules of gas are trapped in the cages constituted by water molecules [1]. The stable existence of gas hydrates has been widely discovered in the marine sediments and under the arctic permafrost regions [2]. Natural gas hydrate has been regarded as an important future energy for its high-energy density and the distribution of the gas hydrate is wider than both the conventional and unconventional energy resource [3]. In addition, gas hydrate technology has been successfully applied in the process of the hydrogen storage [4], sea water desalination [5], and the capture of carbon dioxide [6]. The difficulty with exploiting the gas hydrate is that this resource exists as solid state and is not suitable for the conventional techniques of recovering natural gas and oil.

Depressurization has been widely proven to be an effective method for hydrate dissociation [7–12]. The advantage of the depressurization method is the least energy input, easy operation, and high energy efficiency [13,14]. Japan carried out the hydrate exploitation test by the depressurization method at the Nankai Trough during March 12–16 in 2013, which was the first field test of gas production from the marine hydrate deposit [15]. In addition, the depressurization technology has also been successfully used in the gas production test of the permafrost hydrate at the Mackenzie Delta, North Slope, Alaska [16]. However, the single depressurization confronts the problem of limited sensible heat because the heat for hydrate dissociation is absorbed from the ambient environment [17,18]. That is to say, the gas production rate declines to very low level when the sensible heat of the hydrate reservoir is exhausted [19]. Furthermore, the problems of ice block, secondary hydrate formation, and sand clogging come with single depressurization [20,21].

Thermal stimulation can solve the problem of limited heat supply, ice blockage and second hydrate formation by depressurization [22–25]. The experimental model of Tang et al. [26] showed that the hydrate can be effectively dissociated by thermal stimulation. However, the energy efficiency is very low by the pure thermal stimulation because most of the input energy is absorbed by water and the hydrate reservoir [27]. The combined method can

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take advantage of the merits of both the depressurization and the thermal stimulation. In addition, the combination of the depressurization and thermal stimulation has been proposed to be a favorable method for hydrate dissociation by the experimental and numerical investigations [28–31].

Not only the dissociation method plays important role for gas production, but also the well configuration affects the gas production process dramatically. The numerical study of Moridis et al. [32] showed that the horizontal wells had advantage of higher production efficiency over the vertical wells. Additionally, the experimental investigation in a pilot-scale hydrate simulator by Feng et al. [33] indicated that the horizontal well pattern obtained a higher gas production rate and heat transfer rate than that of the vertical well pattern. Moreover, Wang et al. [34] showed that the production efficiency with the multi-well configuration was higher than that of the single well configuration.

Although the practical field tests have been implemented in the permafrost area and the marine sediment, the regular and long-term field tests are unrealistic because of the huge cost and the time-consuming preparation. Therefore, the experimental research in laboratory still plays key role on the exploitation project of the gas hydrate. Numerical simulation is another indispensable research technique for the function of prediction and computation. As one of the classical and representative simulator, the TOUGH + HYDRATE (T + H) simulator has been widely used in the research of hydrate exploitation in marine [35–37] and permafrost areas [7,38,39]. Moreover, this T + H code has been successfully validated by the experiments of hydrate dissociation with single well by depressurization [40] and the thermal huff and puff [41]. However, the numerical study of the hydrate dissociation in the laboratory scale with the dual horizontal wells has not yet been carried out.

Under these circumstances, we aimed to perform the study of the hydrate dissociation process by depressurization in conjunction with warm water stimulation using dual horizontal wells in a CHS (Cubic Hydrate Simulator). Furthermore, the corresponding numerical investigation was carried out by the T + H simulator, and the results of the experimental study and numerical simulation were compared. In order to reduce energy loss, the low-temperature water (22 °C) stimulation was applied in this work. In addition, the sensitivity analyses of the temperatures for warm water stimulation and the intrinsic permeabilities of the sediments were carried out.

2. Experiment

2.1. Experimental apparatus

Fig. 1 shows the schematic of the experimental apparatus. The detailed information of the CHS has been introduced in our previous work [42]. The CHS is a cubic stainless steel reactor with the maximum working pressure of 30 MPa. The side length of the CHS is 0.18 m and the effective volume is 5.832 L. To ensure the low-temperature environment for hydrate formation, the reactor is surrounded by a water jacket (−15 to 30 °C, ±0.1 °C). An “Inlet Pressure” transducer and an “Outlet Pressure” transducer are situated at the bottom and the top of the CHS, respectively, for the sake of measuring the system pressure at the same time. In addition, a back-pressure regulator is connected into the outlet valve to control the working pressure of the experiment. The amounts of the gas injection and production are measured by two gas flow meters which are placed at the inlet and the outlet valve, respectively. The mass of the produced water is weighed by a balance.

Fig. 2 shows the schematic of the inner structure of the CHS, the well configuration and the distribution of the thermal couples. As shown, the CHS is equidistantly divided into four regions by three horizontal layers. There are 25 ($5 \times 5 = 25$) thermal couples on each layer, the distance of every two thermal couples at each direction is 45 mm. The name of the thermal couple T 25A means the 25th thermal couple situated on Layer A. The naming rule of the rest thermal couples is in accordance with that of T 25A. The well configuration in this work is set as dual horizontal wells. As shown in Fig. 2, the injected fluid is injected from the lower horizontal well (Well HC), and the produced gas and water are pumped out from the upper horizontal well (Well HA). There are 4 grooves evenly distributed along the circumference of the well. The water is injected through the grooves into the porous media.

2.2. Experimental procedure

The experimental procedure can be divided into two parts of hydrate formation and dissociation. The experimental conditions and parameters of hydrate formation and dissociation are shown in Table 1. The detailed information of the hydrate formation process and calculation method has been reported in our previous studies [33,34]. Firstly, the CHS was stuffed with raw quartz sand (the particle diameter is from 300 to 450 μm). The residual gas was

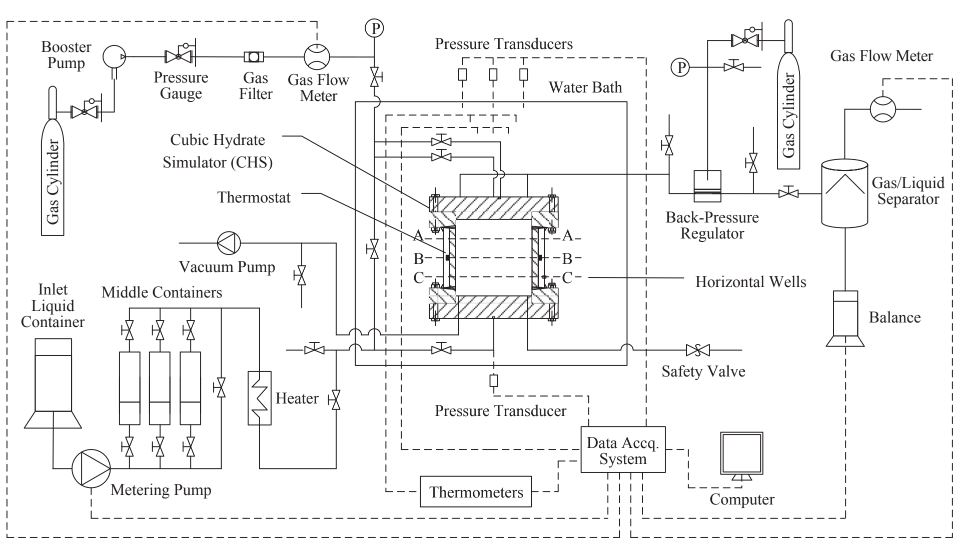

Fig. 1. Schematic of experimental apparatus.