Fuel 117 (2014) 688–696

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Experimental study on the hydrate dissociation in porous media by five-spot thermal huff and puff method

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HIGHLIGHTS

- The production behaviors of methane hydrate are investigated in the 3-D simulator.
- The different methods are used for hydrate production.
- The gas/water production, efficiency, recovery, and production rate are analyzed.
- The heat stimulation combining depressurization in 5-spot well is the optimal method.

ARTICLE INFO

Article history:
Received 25 July 2013
Received in revised form 20 September 2013
Accepted 29 September 2013
Available online 10 October 2013

Keywords:
Methane hydrate
Three-dimensional
Thermal stimulation
Depressurization
Thermal huff and puff

ABSTRACT

A novel method for hydrate production named "Five-spot thermal huff and puff (HP-5S)" is designed and employed to investigate the behaviors of hydrate dissociation in the Cubic Hydrate Simulator (CHS). This method uses the thermal huff and puff method in a five-spot well system. In addition, the experiments with the methods of the five-spot thermal huff and puff in conjunction with depressurization (HP-5S-D), the heat stimulation with a five-spot well (HS-5S), the heat stimulation in conjunction with depressurization with a five-spot well (HS-5S-D), the thermal huff and puff (HP), and the huff and puff in conjunction with depressurization (HP-D), are also carried out in this work. The energy efficiencies, thermal efficiencies, gas recoveries, and average gas production rates are used to evaluate these production methods. The analysis of hydrate decomposition shows that the thermal huff and puff method in a five-spot well system is superior to that in a single vertical well on the aspects of the energy efficiency, thermal efficiency, gas recovery, and average gas production rate. The HP-5S-D method, which can obtain the highest gas recovery, thermal efficiency, and energy efficiency, is the optimal method for hydrate production in this work.

1. Introduction

Natural gas hydrates are solid crystalline compounds in which the gas molecules are trapped in the crystal lattices formed by hydrogen-bonded water molecules [1]. Natural gas mainly consists of methane, and also consists of other hydrocarbon gases like ethane, propane, butane and non-hydrocarbon gases. One volume of methane hydrate can release 164 volumes of methane at standard condition. The field expeditions have provided the understanding that gas hydrates occur in a wide variety of geological settings. Although the current estimates of the in-place amounts vary widely, the consensus is that the total volume of methane housed in gas hydrate is certainly very large as compared to other global methane reservoir [2].

Methods for recovering natural gas from hydrates are various and are still developing. For now, the most practical methods are as follows: (1) the thermal stimulation [3–5], (2) the depressurization [6–8], (3) the chemical injection [9], and (4) CO_2 replacement [10–11]. Till now, field tests on methane hydrate production under varied methods had been carried out around the world [12]. The method combining the depressurization and the thermal stimulation was demonstrated to be superior in the Mallik 2002 well [13]. Meanwhile, in the winter of 2007 on the North Slope of Alaska, hydrate was dissociated by depressurization, and again indicated that simple depressurization was an effective method to produce gas hydrate [14]. The latest news reported that the world's first offshore experiment producing gas from methane hydrate was carried out by using a depressurization method in the Nankai Trough, Japan [15].

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0016-2361/$ - see front matter
http://dx.doi.org/10.1016/j.fuel.2013.09.088

In laboratory, the experimental studies of the hydrate dissociation under different methods in porous media using 1-D [4,16], 2-D [17], and 3-D [18–21] systems had been reported. In recent years, to test realistic production methods, more experimental vessels for the hydrate production investigation were designed and manufactured, and the experimental systems were getting bigger and more sophisticated. Pang et al. [22] had investigated the hydrate dissociation by the hot water injection in a 10 L reactor and reported that the heat transfer and thermal driving forces are the determining factors of the hydrate dissociation. Schicks et al. [23] designed a large system, which is the Large Laboratory Reservoir Simulator (LARS) with a volume of 216 L located in a water–glycol jacket for controlling temperature and pressure. Yuan et al. [24] built a three-dimensional middle-size reactor with effective height of 100 mm and inner diameter of 300 mm to study the different methods for methane extraction from hydrate reservoir. The depressurization method [25], the hot-water cyclic injection method [21], the ethylene glycol injection method [20], and the CO_2 replacement method [24] had already been tested in this reactor. A high-pressure vessel with the volume of 1710 L and weight of 9900 kg had been built for simulating the exploitation of a methane hydrate reservoir at the eastern Nankai Trough area [26].

In our previous work, a three-dimensional cubic pressure vessel (5.8 L, the Cubic Hydrate Simulator (CHS) [18,19,27]) was designed and manufactured for investigating the production processes of hydrate. The thermal huff and puff method with one vertical well and the heat stimulation method with a five-spot well for hydrate dissociation had been separately investigated in this vessel. The results indicated that the hydrates in the reservoir cannot be completely dissociated by the thermal huff and puff method with a single well, because there was a maximum region in the hydrate dissociation. By the heat stimulation method with a five-spot well, the heat injection was uninterrupted, thus the energy efficiency was relative low.

In this work, a novel hydrate production method, which combines the above two methods, named "five-spot thermal huff and puff (HP-5S)" is designed and tested to investigate the behaviors of hydrate dissociation in the CHS. In addition, the five-spot thermal huff and puff method in conjunction with depressurization (HP-5S-D), the heat stimulation method with a five-spot well (HS-5S), the heat stimulation method in conjunction with depressurization with a five-spot well (HS-5S-D), thermal huff and puff method (HP), and huff and puff in conjunction with depressurization method (HP-D), are also performed. Furthermore, the advantages and disadvantages of these production methods are evaluated with the energy efficiencies, thermal efficiencies, gas recoveries, and average gas production rates, and thus, the optimal production method is determined.

2. Experiment

2.1. Experimental apparatus

The details of the CHS have been reported in our previous work. The schematic of the CHS is shown in Fig. 1. The experimental apparatus involves a high-pressure reactor, a water bath around the reactor, a back-pressure regulator, a gas and liquid injection equipment, a water/gas separator, a data acquisition system, and some measurement units. The high-pressure reactor (cubic inside, volume of 5.8 L, maximum pressure of 25 MPa) is the core component of the apparatus. The distributions of the thermocouples (measure temperatures) and wellheads within the CHS are shown in Fig. 2. As seen in Fig. 2, there are 25 × 3 thermocouples, two central vertical wells, and four vertical wells in the four corners of the CHS. There are three layers, which divide the measuring points and the wellheads, named: Layer A, Layer B, and Layer C, respectively. In this work, during the process of heat injection, the inlet for the heat injection is the V_I in the Layer C along the centerline of the reactor, and the outlets for the gas/water production are the V_1–V_4 in the layer A; during the process of depressurization, the outlet is the V_P in the layer A along the centerline.

2.2. Experimental procedure

Detailed descriptions of the formation process for methane hydrate have also been introduced in previous studies [6,27]. The porous sediment used in this work was the quartz sand with grain sizes of 300–450 μm. Before the experiments start, the silica sand was placed in the vessels as the porous media and porosities were approximately 48%. 1219 ml of the deionized water and 16.8 mol of the methane were injected to the CHS for hydrate formation. After 14–20 days for the hydrate formation, hydrate samples were ready to be tested for methane production [28]. Before hydrate production, the initial hydrate saturation (volume) was calculated as approximately 31.0%, using the method of Linga et al. [29]. During the hydrate production, the temperature of the water bath was maintained at 8.0 °C. The initial conditions for all of the experiments in this work were identical. These conditions corresponded to the conditions of the hydrate reservoir in the Shenhu area of South China Sea [30]. At the working temperature (8.0 °C), the equilibrium pressure was calculated to be 5.7 MPa. The different production pressures (6.5 MPa and 5.6 MPa) resulted in the different equilibrium hydrate dissociation temperatures which were calculated to be 9.3 °C and 7.9 °C, respectively, by the fugacity model by Li et al. [31]. In the preheater, the temperature of deionized water was raised to the injection temperature (T_{inj} = 130 °C) in this work. In addition, the state of water at 130 °C and over 5.6 MPa is still liquid. The hot water injection rate (R_{inj} = 40 ml/min) was set by the metering pump in this work. After preheating, the heated water was injected through the inlet. Afterward, the experiments of hydrate dissociation with different methods were carried out. Finally, after finishing the experiment, the residual gas was released and the system pressure decreased to zero gradually. In the above stages, the data were recorded by the data acquisition system in real time. In this paper, the behaviors of hydrate production in the porous sediment with different methods were studied by six experiments. The methods for hydrate dissociation are described as follows.

2.2.1. Heat stimulation with a five-spot well (HS-5S)

During the HS-5S (5S means five-spot well) method, the gas production pressures (6.5 MPa) kept steady, which were higher than the equilibrium pressure. The experiment started by injecting hot water through the injection well (V_I) into the CHS. Meanwhile, the valves of the production wells (V_1–V_4) were opened, and then the gas production began. After more than 1 h of hot water injection, the rate of gas production dropped to approximately 0. It was believed that no more hydrate is decomposed in the CHS. Therefore, the entire experimental process ended.

2.2.2. Heat stimulation in conjunction with depressurization with five-spot well (HS-5S-D)

The HS-5S-D method consists of two stages: pre-depressurization stage and heat stimulation stage. During the pre-depressurization phase, the production wells were opened to release gas and water until the system pressure declines to the set pressure (5.6 MPa), which was lower than the equilibrium pressure (5.7 MPa). During the heat stimulation phase, the process was similar to that of the HS-5S method. The difference was that the production pressure in the HS-5S-D method was below the equilibrium pressure.