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Experimental investigation of optimization of well spacing for gas recovery from methane hydrate reservoir in sandy sediment by heat stimulation ☆

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HIGHLIGHTS

- Hydrate dissociation by heat stimulation with different well-spacing are studied.
- Optimized well-spacing should equal to the maximum range of hydrate dissociation.
- An integrated factor is proposed for evaluating the gas recovery method.
- Maximum range for hydrate dissociation in reservoir by heat stimulation is verified.

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ABSTRACT

Due to the vast amount of recoverable natural gas predicated (~3000 TCM) in natural gas hydrate on earth, natural gas hydrate has the potential to become the next generation of unconventional source of fuel. Recently years, laboratory researches are still underway to advance our understanding of the theory and technology for natural gas hydrate exploitation. In this work, experiments of methane hydrate dissociation by heat stimulation with different well-spacing were firstly performed in the Cubic Hydrate Simulator (CHS). The five-spot vertical wells (5-wells) and the dual vertical wells (D-wells) were applied as the multi-well strategies. The well spacing of D-wells is twice as larger as that of the 5-wells. The influences of well spacing on the production behaviors and the heat transfer characteristics during hydrate dissociation are analyzed. The experimental results indicate that a maximum range for hydrate dissociation exists during hydrate dissociation by heat stimulation method, which is in direct proportion to the heat injection rate (R_{inj}). The optimized well-spacing should equal to the maximum range of hydrate dissociation. For maximizing average gas production rate per well, the larger well spacing and the higher R_{inj} benefit for gas recovery. On the other hand, for minimizing the heat consumption per unit of gas production (H_{GP}), the moderate R_{inj} and the shorter well spacing benefit for gas recovery. In order to evaluate the gas recovery by heat stimulation with different well spacing and R_{inj}, an evaluation factor is firstly proposed, which considers the combined effect of the gas production rate per well, the H_{GP}, and the hydrate dissociation ratio. By calculation, the optimal experimental conditions for hydrate recovery in experiments are the injection rate of 40 mL/min with the longer well spacing (D-wells). The study of temperature distribution verifies the maximum range for hydrate dissociation in reservoir by heat stimulation.

1. Introduction

Nowadays, approximately 85% of the primary energy is provided by fossil fuels in the world [1,2]. However, conventional fossil fuel resources are being exhausted. On the other hand, the technologies of renewable energy are still developing. Therefore,

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a “bridge” between the conventional fossil fuel and the renewable energy is essential and urgent to be discovered. Natural gas hydrate (NGH), which is a kind of unconventional fossil fuel, are generally considered as a potential energy for the future economic development [3,4]. The general characteristics for the NGH are high-energy density and huge reserves. In the last decade, the NGH researches have been developed rapidly. Nowadays, developing methods for methane recovery from the hydrate reservoirs is attracting considerable attention of the researchers and governments all over the world.

NGH, which composed of water cages and gas molecules, is a kind of clathrate crystalline compound. The water cages are stabilized by hydrogen bonding. The majority of the gas molecule is methane (over 90%), but other hydrocarbon gases may also exist [4–6]. Up to now, over 230 NGH potential deposits have been identified globally. NGH could exist at subsurface depths ranging from approximately 130 to 1100 m in the permafrost regions, and below the sea level with the water depths between 800 and 4000 m in offshore continental margins. The amounts of methane stored in NGH bearing oceanic sediments are enormous, and the global speculative estimates of the NGH reserves ranging from 3114 to 7,634,000 TCM [4–7]. Therefore, it is considered to be a potential energy source [8]. Furthermore, hydrate based technology also can be used in the field of the CO_2 capture and storage [9], the hydrogen storage [10,11], the sea water desalination [12], and flow assurance [13,14].

Recently, mainly methods for gas recovery from hydrate reservoirs are based on in-situ hydrate dissociation by shifting the thermodynamic equilibrium firstly and then extracting gas from sediment. The methods based on in-situ hydrate dissociation mainly are (1) the depressurization method, which by reducing hydrate reservoir pressure below the hydrate decomposition pressure to dissociate the hydrate [15,16], (2) the thermal stimulation method, which by heating the hydrate reservoir temperatures above the hydrate decomposition temperature to dissociate the hydrate [17–19], (3) the chemical injection method, which by injecting the chemicals into the reservoir to promote the hydrate decomposition [20,21]. In addition, some other methods are also developed, for example, the CO_2 replacement method, which by injecting the CO_2 into the hydrate reservoirs to replace the methane from hydrate [22,23]. Until now, there were just 4 field tests for gas production from hydrate reservoirs. In the field test at the Mackenzie Delta, Northwest Territories in Canada, the thermal stimulation and depressurization method were applied for hydrate dissociation [6]. During the offshore test at the Nankai Trough in Japan, the depressurization method was tested for over 6 days and about $1.3 * 10^5\ m^3$ natural gas was produced [24]. The field tests carried out have demonstrated the possibility of recovering natural gas from hydrate reservoir, however, how to recovery energy in a more effective and efficient way is still challenging. Furthermore, these field trials involve high capital investment, long planning and execution period, arduous working environment, and unpredictable operations, therefore require strong collaboration effort between government, corporations and research institutions. Thus, the laboratory researches, especially the large scale laboratory researches, are underway to understand the hydrate dissociation characteristics as well as to devise the methods and equipment for realizing the potential of energy recovery from natural gas hydrate [6,25–28].

In last decades, the researches of the laboratory experiments for hydrate dissociation focus on the fundamental researches during hydrate dissociation and the method optimization for the gas recovery from natural gas hydrate [29]. Several large scale laboratory set-ups, which were built in the USA [30], China [31], Germany [32], and Japan [24], for mimicking field tests of gas production from hydrate reservoir have been reported [33]. The large scale researches are employed to develop the efficient and sustainable gas production methods in the hydrate reservoir. The coupled phase change process, heat/mass transfer, and gas/water production characteristics during hydrate dissociation by different methods can be investigated by the experiments [34,35]. Serials of the innovative methods for gas production from hydrate are investigated in these large scale experiments, for example, the deep depressurization method [16], the liquid CO_2 replacement [36], the in-situ catalytic combustion [37], the depressurization combined with warm water stimulation method [38,39], and the five-spot thermal huff and puff method [17]. Furthermore, the dissociation method conditions can be optimized by the experimental investigations, such as the production pressure, the heat injection temperature, and the heat injection rate [28,38].

Most of the large scale experimental set-ups for the hydrate investigation have only one mimical well or even have no well. Therefore, a few investigations focus on gas production from hydrate reservoir with multi-wells system. However, many gas recovery methods, especially heat stimulation method and chemical injection method, should be applied in multi-wells system, which includes an injection well and a production well at least. The Cubic Hydrate Stimulator (CHS), which is designed and built by our group from 2009, installs 9 vertical wells and 9 horizontal wells in the apparatus. In our previous work, many gas production methods by multi-wells system have been developed and investigated in the CHS, such as the five-spot thermal stimulation method using 5-wells system and depressurization in conjunction with warm water stimulation using duel horizontal wells system. In the multi-wells system, the distance between the wells obviously is a key parameter to influence the production behaviors for hydrate reservoir. However, few large experimental investigations of the influence of well spacing on the gas recovery from hydrate reservoir are reported.

In this work, experiments of the hydrate dissociation by heat stimulation with different well spacing are firstly performed in the CHS. The well systems with different well spacing, which are five-spot vertical wells (5-wells) and dual vertical wells (D-wells), are applied in the experiments. The well spacing of D-wells is twice as larger as that of the 5-wells. The hydrate dissociation experiments, with the water temperature of 160 °C and water injection rate ranged from 10 mL/min to 40 mL/min, are conducted in the CHS using these multi-wells systems, respectively. The influences of well spacing on the production behaviors, the heat transfer characteristics, and the production efficiency are analysis by the experiments, and the well spacing of heat stimulation method is optimized by the experimental results.

2. Experiments

2.1. Experimental apparatus

Fig. 1 is the apparatus schematic. 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 measuring units. The core component of the apparatus is the high-pressure reactor, Cubic Hydrate Simulator (CHS), which is cubic inside and made of 316 stainless steel. The inner length is 180 mm and the inner volume is 5.8 L. The apparatus was encircled by a water bath (−15 to 30 °C, ±0.1 °C), which constitutes the ambient temperature control system. The details of the experimental apparatus have also been reported in the previous work [31].

Fig. 2 gives the schematic of distributions of measuring points and well configuration within the CHS. As shown in this figure,

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