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Production behavior of methane hydrate in porous media using huff and puff method in a novel three-dimensional simulator

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ABSTRACT

The gas production behavior of methane hydrate in porous media using the huff and puff method was investigated in the Cubic Hydrate Simulator (CHS), a novel developed three-dimensional 5.8-L cubic pressure vessel. Three horizontal layers equally divide the CHS into four regions. A 9-spot distribution of the vertical wells, a single horizontal well and a 25-spot distribution of the thermometers are arranged on each layer, respectively. The vertical wells at the axis of the CHS were used as the injection and production wells. The huff and puff method includes the injection, soaking and production stages. The amount of water injected and produced, the gas production rate, the percentage of the hydrate dissociation and the gas-to-water ratio were evaluated. Under the thermodynamic conditions in this work, the gas production from the sediment in this work using the huff and puff method is economically profitable from the relative criterion point of view. The sensitivity analysis demonstrates the dependence of the gas production on the initial hydrate saturation, and the temperature and the injection rate of the injected hot water.

1. Introduction

Natural gas hydrates (NGH) are crystalline solids composed of water and gas. The gas molecules (guests) are trapped in water cavities (host) that are composed of hydrogen-bonded water molecules. Typical natural gas molecules include methane, ethane, propane, and carbon dioxide etc. Natural gas hydrate deposits involve mainly CH_4, and occur in the permafrost and in deep ocean sediments, where the necessary conditions of low temperatures and high pressures exist for hydrate stability [1]. Estimates of the world hydrate reserves are very high, and vary from 0.2×10^{15}–120×10^{15} m^3 of methane at STP (Standard Temperature and Pressure). However, even with the most conservative estimates, it is clear that the energy in these hydrate deposits is likely to be significant compared to all other fossil fuel deposits [1], and was considered to be a potential strategic energy resource [2–5].

There are three main methods for gas production from the hydrate deposit: 1) Depressurization [6–11], to decrease the deposit pressure below the hydrate dissociation pressure at a specified temperature; 2) Thermal stimulation [6,12–14], to heat the deposit above the hydrate dissociation temperature with the hot water, hot brine or steam injection; 3) Thermodynamic inhibitor injection [15–17], to inject the chemicals, such as the salts and the alcohols to shift the hydrate pressure–temperature equilibrium conditions; 4) A combination of these methods [18–20]. Of the above single methods for hydrate dissociation for gas production, the depressurization appears to be the most efficient one [5,21,22], and the thermal stimulation could be the auxiliary method [5,10]. The Mallik 2002 well demonstrated the proof of the concept that it is possible to recover energy from permafrost hydrates combining the dissociation techniques of the depressurization and the thermal stimulation [1]. Experimental investigations of the hydrate dissociation behaviors under the depressurization or thermal stimulation in the sediments using one-dimensional [6,12,14] and two-dimensional apparatuses [23] have been reported. Actually, the hydrate deposit in the nature is a three-dimensional (3-D) reservoir. In order to investigate into the gas production characteristics in a 3-D reservoir, it is quite significant to simulate the hydrate dissociation behaviors in the 3-D experimental apparatus. However, so far, there are few reports on this aspect.

The huff and puff method, also known as the cyclic steam stimulation (CSS), was accidentally discovered by ShellOil Company in 1960 during a Venezuela recovery project, and is widely used in the oil industry to enhance oil recovery [24–26]. The hot water, hot brine or steam huff and puff method is a special form of the combination of depressurization and thermal stimulation methods

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for gas production from hydrate deposit. A numerical simulation of gas production from marine gas hydrate deposit using the huff and puff method has been used to investigate into the gas production strategy in the Shenhu Area of the South China Sea [20].

In this work, the Cubic Hydrate Simulator (CHS), a novel three-dimensional 5.8-L cubic pressure vessel has been developed for the production of the gas hydrate. The gas production behavior of methane hydrate in the porous media using the huff and puff method was investigated in the CHS. Vertical wells at the axis of the CHS are used as the injection and the production wells.

2. Experiment

2.1. Experimental apparatus

The schematic of the experimental apparatus used in this work is shown in Fig. 1. The CHS is made of stainless steel, and can withstand pressures of up to 30 MPa. The low temperatures required for the experiments are achieved by placing the CHS vessel in a water bath. Fig. 2 shows the schematic of the layers and the well design of the CHS. The CHS is a cubic pressure vessel with the internal length of side of 0.18 m and the inner volume of 5.8-L. As shown in Figs. 1 and 2, there are 3 horizontal layers named Layers A–A, B–B and C–C inside the vessel, which equally divide the cubic vessel into 4 regions. In other words, the distance between the Layer A–A and Layer B–B is 0.045 m, a quarter of the internal length of side of the CHS, which is the same with that between the Layer B–B and Layer C–C, while the Layer B–B is in the middle of the CHS. As shown in Fig. 2, a 9-spot distribution of the vertical wells is fixed in the top flange (the Top Square) of the CHS, and there are 3 vertical wells at each spot (V1, V2, … V9), which extend into the vessel to the Layers A–A, B–B and C–C, respectively. As a typical example, it is shown in Fig. 2 that the Wells V5A, V5B and V5C are all placed on the spot V5, and the bottoms of these wells are on the Layers A–A, B–B and C–C, respectively. In general, a total of 27 vertical wells are distributed in the CHS, and each of them (except the 3 vertical wells, Wells V5A, V5B and V5C at the axis) is immediately close to the inside edge of the CHS, and the bottom of each well is right on the corresponding layer. As shown in Fig. 2, in the Right Square of the CHS, 3 horizontal wells, the Wells HA, HB and HC, are inserted into the spots H1, H2 and H3 on the Layers A–A, B–B and C–C, respectively. Each horizontal well is extended to the inside surface of the Left Square of the CHS. Fig. 3 shows the schematic of the distribution of the thermometers (the temperature measuring spots) in the CHS. There are 25 thermometers evenly distributed on each layer, with a total of 75 spots in the CHS. In other words, on each layer (Layers A–A, B–B and C–C), it is a 25-spot distribution of the thermometers (T1–T25), with T13 at the center and T1, T5, T21 and T25 at the corner. The thermometers except those at T7–T9, T12–T14 and T17–T19 are immediately close to the inside edge of the CHS. The thermometers at the same spots are distinguished by the different layers, for example, as shown in Fig. 3, the 21st thermometer on Layer A–A is called T21A, and those on the Layer B–B and Layer C–C are T21B and T21C, respectively. A pressure transducer at the center of the bottom of the CHS (the "Inlet Pressure") is used to measure the pressure of the base of the Hydrate-Bearing Layer (HBL). And another pressure transducer (the "Outlet Pressure") is placed at the production well. A sampling valve is placed on each layer. A safety valve and a vacuum pump are connected to the CHS.

The thermometers are Pt100 with the range of −20–200 °C, ±0.1° C. The pressure transducers are TRAGAG NAT 8251.84.2517, 0–40 MPa, ±0.1%. Two gas flow meters, which are used to measure the cumulative gas injected into the CHS, the gas production rate and the cumulative gas produced from the vessel, are both of D07-11CM, 0–10 L/min, ±2% from "seven star company". The thermometers, pressure transducers, gas flow meters, were calibrated using a mercury thermometer with the tolerance of ±0.01° C, a pressure test gauge with the error of ±0.05%, and a wet gas meter with the accuracy of ±10 ml/min, respectively.

A metering pump "Beijing Chuangxintongheng" HPLC P3000A with the range of 50 ml/min can withstand pressures of up to 30 MPa. An inlet liquid container with the inner volume of 10 L is used to contain the deionized water used in the experiments. In

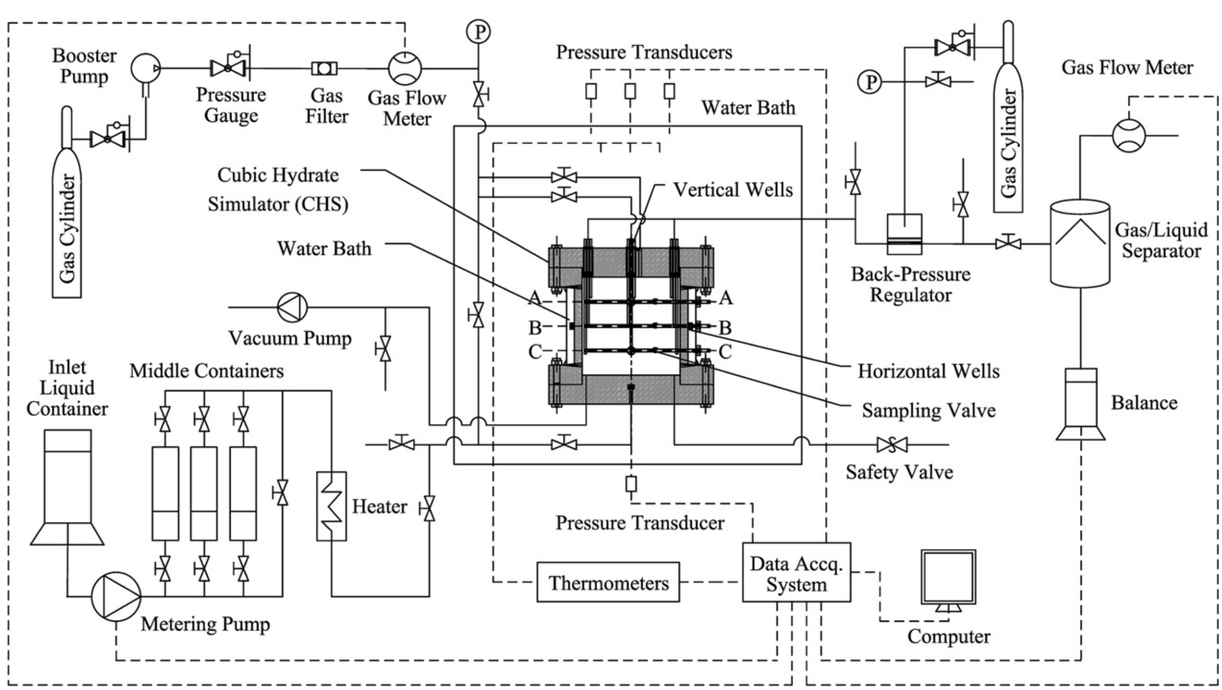

Fig. 1. Schematic of the experimental apparatus.