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Numerical simulation of Class 3 hydrate reservoirs exploiting using horizontal well by depressurization and thermal co-stimulation

Shengwen Yang, Xuemei Lang, Yanhong Wang, Yonggang Wen, Shuanshi Fan *

Key Laboratory of Enhanced Heat Transfer and Energy Conversation, Ministry of Education, South China University of Technology, Guangzhou 510640, Guangdong Province, People's Republic of China

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ABSTRACT

Class 3 hydrate reservoirs exploiting using horizontal well by depressurization and thermal co-stimulation was simulated using the HydarteResSim code. Results showed that more than 20% of hydrates in the reservoirs had been dissociated within 450 days at the well temperature of 42 °C and well pressure of $0.1P_0$, $0.2P_0$ (P_0 is the initial pressure of the reservoirs, simplifying 42 °C & $0.1P_0$, 42 °C & $0.2P_0$). While the production behavior of 42 °C & $0.5P_0$, 42 °C & $0.8P_0$ were not so exciting. In order to understand the production character of the well in long term, the cross section of 1 m length reservoirs was simulated. Simulation results showed that 4.5×10^5 m^3 gas would be collected within 4500 days and 1.1×10^6 kg water could be produced within 1500 days in the well at 42 °C & $0.1P_0$. 3.5×10^5 m^3 gas would be collected within 8500 days and 1.1×10^6 kg water could be produced within 1500 days in the well at 42 °C & $0.2P_0$. The heat flow was 1620 W at the beginning and then decreased rapidly in the two cases. For reservoirs of 1495.2 m in length, about 6.7×10^8 m^3 and 5.3×10^8 m^3 gas would be collected in the well corresponding to conditions of 42 °C & $0.1P_0$, and 42 °C & $0.2P_0$.

1. Introduction

Natural gas hydrates are clathrate nonstoichiometric crystal compound. And hydrate reservoirs exist in the low temperature and high pressure geologic zone, such as the permafrost and marine sediments. It is believed that the amount of carbon in gas hydrate reservoirs on the earth is twice that in proven fossil fuels [1,2]. Many countries paid great attention to hydrates with the traditional fossil energy exhaustion and its wide range of applications developed in many field [3]. America had made all-round studies on hydrate dissociation in industry level [4–7]. Japan had made long-term strategies on the gas hydrates exploitation from Nankai Trough, and they hoped the hydrate reservoirs in Nankai Trough could be dissociated in the near future [8,9]. It is greatly expected that hydrate reservoirs in **nature** can be dissociated in the near future with the deep-going study of hydrate reservoirs around the world [10,11].

Moridis Classified hydrate reservoirs into 4 types [6,11,12], according to reservoirs distributions, reservoir structures, hydrate components and bearing geophysical properties. Class 1 hydrates are composed of two layers. The underlying layer is two phases fluid zone with free gas and water, and the hydrates overlying layer is saturated with water and hydrates (Class 1W) or gas and hydrates (Class 1G) [13]. Class 2 deposits are also comprised of two zones, an overlying hydrates bearing and a mobile water zone. Class 3 deposits consist of three zones. The top and bottom are impermeability layers, and the middle layer is hydrate reservoirs layer. Class 4 deposits contain one zone, in which the hydrate saturation is very low (less than 0.1) and hydrates are dispersed in the deposits. Hence, it is worthless to exploit Class 4 deposits with the present technology for the small amount of hydrates in each unit volume of reservoirs [14]. The Class 1,2 hydrates with the mobile fluid in the under layers, the Class 1G hydrates can be produced by depressurization method[13], and Class 1W and Class 2 hydrates can be produced in depressurization method with the help of thermal stimulation, and simulations [15–17] have testified that these two kind of hydrates are worthy to extract methane.

For Class 3 hydrate reservoirs, it is difficult to extract natural gas using single stimulation method through vertical well for their low permeability in the hydrate bearing internal, compared to Class 1, and Class 2 hydrates. It was controversial whether Class 3 hydrates are worthy to exploit considering low economy and energy efficiency [18,19]. Moridis studied the hydrates dissociation by step-by-step depressurization production method, and the results showed that the vertical well could be used for Class 3 hydrates exploitation if the correct strategy was taken. However, the production simulation carried out by Moridis and Reagan only lasted about 1500 days in industry level [18]. Su et al. [20] and Myshakin et al. [21] employed the depressurization and thermal stimulation method to investigate vertical well hydrates dissociation, and found that the gas released rate was too small to reach

* Corresponding author. Tel./fax: +86 20 22236581.
E-mail address: ssfan@scut.edu.cn (S. Fan).

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industry-scale commercial production. Li et al attempted to produce gas by depressurization and the pull and hull method in horizontal well, but the results were not as satisfactory as expected [19,22–24]. Bai et al. used the combination method of warm water flooding and depressurization to produce gas from Class 3 hydrate reservoirs by vertical well. Their research showed that the combination method contributed more to enhancing the stable period at high gas released rate than single stimulation method [25,26]. At the same time, Li et al. tried the lab experiment research in hot-brine injection and got the conclusion that the combine of thermal and depressurization would be better for gas production from hydrate reservoirs [27]. A good introduction and summary in hydrate dissociation can be obtained from Ahmadi [28].

From the above analysis, gas production from Class 3 hydrate reservoirs by the vertical well is not suitable because of the single hydrate bearing internal and two impermeability layers structure of Class 3 hydrate reservoirs. So the horizontal well can be more favorable for gas extraction. At the same time, studies showed that depressurization can be particularly important for gas production from hydrate reservoirs for their hydrate dissociation and temperature infiltrating effect [29]. In this paper, we utilized the depressurization and thermal co-stimulation to exploit natural gas from Class 3 hydrate reservoirs using horizontal well, aiming to work out a feasible extraction strategy for Class 3 hydrates in industry level.

2. Physical model and gas production strategy

2.1. Reservoirs properties

Fig. 1 shows the structure of Class 3 hydrate reservoirs with one impermeable top cover layer, one impermeable bottom layer, and one hydrate bearing layer. Many factors can affect the gas production from hydrate reservoirs [6]. In this paper, we just discuss those properties that greatly affect the economy and energy efficiency for gas production from hydrate reservoirs. The permeability of the top and bottom layers is impervious in Moridis' definition. While the permeability of the top and bottom layer in this work is different from that of the hydrate bearing layer, and the Van Genuchten Capillary pressure model would be used [30].

A Class 3 hydrate reservoirs model was built based on the data of Shenhu site SH7 area hydrate reservoirs in China. The hydrate bearing layer exists 1108–1245 m under the water with thickness of 10–43 m (20 m of hydrate bearing layer, 30 m top and 30 m bottom layers were used in this work). The sediment porosity measured from pressure cores is 0.33–0.48 (0.4 was used in hydrate bearing layer, and 0.2 was used in top and bottom layers) and in situ salinity is 0.0290–0.0315 (0.0030 in this paper) in weight

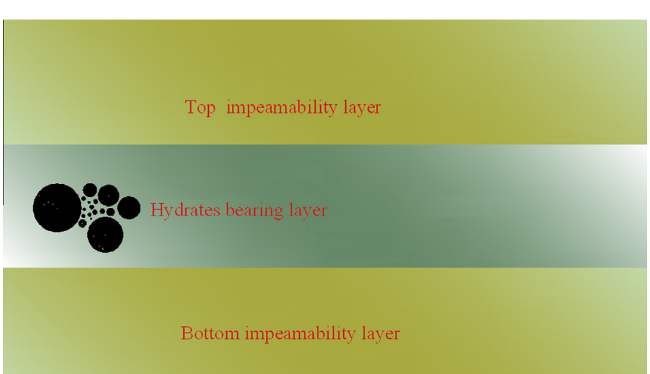

Fig. 1. Class 3 hydrate reservoirs structure characters sketch map defined by Moridis.

[22,23]. Wire-line logging features of site SH7 were described by Wu et al. [31]. Reservoir parameters used in this simulation were shown in Table 1, and the other parameters were set as default in HydrateResSim code [32].

2.2. Reservoirs discretization

The dimension of the studied hydrate reservoirs is 1495.2 × 400 × 80 m. The calculated thickness of the reservoirs in geophysical survey was 80 m. The horizontal dimensions in *X*, *Y* directions were 1495.2 m and 400 m respectively. The value of dimension width, 400 m, was set after referenced Grover' physical model whose value was 350 m in diameter [7]. The horizonal length was set as 1495.2 m to ensure that the reservoirs contain large amount of hydrates, and if correct strategy were taken, large amount of natural gas would be produced. In *X* direction, the total length, 1495.2 m, was divided into 300 grids, where 299 grids are equal-length, i.e., 5 m intervals and 1 grid is 0.2 m which was used to locate the vertical part of well. In *Y* direction, the total width, 400 m, was divided into 3 intervals, i.e., 199.9 m for the two side grids, and 0.2 m for the well in the center. In *Z* direction, the total thickness, 80 m, was divided into 55 intervals and their length ranged from 0.2 m to 1 m for hydrate bearing layer, and 1–2 m for top and bottom layers. The total grids number was 49,500 (55 × 300 × 3). 3D model mesh of the reservoirs was shown in Fig. 2. The Dirichlet conditions of fixed pressure & temperature were applied for the most top-layer and most bottom-layer grids (300 × 3), and Neumann boundary conditions of no fluxes of mass & heat for the boundary grids of the other two directions [32]. The 2D model of a cross section slice with 165 (3 × 55) grids in 1 m length reservoirs is employed for gas collection, water production and heat flow study.

2.3. Well design and production strategy

The cross section dimension of the well is 0.2 × 0.2 m. The well is in "L" form, whose horizontal and vertical length is 1495 m and 40 m, respectively. The vertical part of the well was located in a slice of 0–0.2 m in *X* direction. In *Y* direction, the coordinate was 199.9–200.1 m, and in *Z* direction, and the coordinate was 0 to −40 m. The horizontal part of the well was located in the center of 80 m reservoirs in cross section of 0.2 × 0.2 m (also in the Hydrate bearing layer center), in *X* direction, the coordinate was 0.2–1495.2 m, in *Y* direction, the coordinate was 199.9–200.1 m, and in *Z* direction, the coordinate was −39.9 to −40.1 m. The well profile was shown in Fig. 3.

The simulations were conducted in two steps. Firstly, the 3D model of 80 × 400 × 1495.2 m hydrate reservoirs were studied. Secondly, the 2D cross section 80 × 400 × 1 m reservoirs were used to investigate the fluid behavior and heat flow in the well. Both in the 3D and 2D simulations, the well temperature was set as 42 °C for energy saving, second hydrates & ice formation proof. The well pressure were set as constant value every time. And then repeated simulation by changing pressure value to investigate pressure effect, i.e., $0.1P_0$, $0.2P_0$, $0.5P_0$, $0.8P_0$. So the cost effective production parameters were set as 42 °C & $0.1P_0$, 42 °C & $0.2P_0$, 42 °C & $0.5P_0$ and 42 °C & $0.8P_0$ respectively.

2.4. Numerical simulation code

HydrateResSim is an open source code, a member of TOUTH+-HYDRATE family from the National Energy Technology Laboratory (NETL) developed by Moridis et al. [32]. The code describes the gas-water system in mathematical models which governs the dissociation of methane hydrate reservoirs by depressurization, thermal stimulation, and inhibitor (like sodium chloride, methanol, etc.)