Energy Conversion and Management 108 (2016) 439–445

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Sustainable gas production from methane hydrate reservoirs by the cyclic depressurization method

Yoshihiro Konno [a,*], Yoshihiro Masuda [b,c], Koya Akamine [d], Motoyoshi Naiki [d], Jiro Nagao [a,*]

[a] Methane Hydrate Production Technology Research Group, Research Institute of Energy Frontier, Department of Energy and Environment, National Institute of Advanced Industrial Science and Technology (AIST), 2-17-2-1 Tsukisamu-Higashi, Toyohira-ku, Sapporo 062-8517, Japan

[b] Research into Artifacts, Center for Engineering, The University of Tokyo, Kashiwanoha 5-1-5, Kashiwa, Chiba 277-8568, Japan

[c] Department of System Innovation, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-Ku, Tokyo 113-8656, Japan

[d] Petroleum Engineering & Consulting Department, Japan Oil Engineering Co. Ltd., Kachidoki Sun-Square, 1-7-3 Kachidoki, Chuo-Ku, Tokyo 104-0054, Japan

ARTICLE INFO

Article history:
Received 16 October 2015
Accepted 14 November 2015
Available online 7 December 2015

Keywords:
Gas hydrate
Methane
Production
Depressurization
Numerical simulation

ABSTRACT

The cyclic depressurization method, which uses alternating depressurization and shut-in periods over decades, has been proposed to achieve sustainable gas production from methane hydrate reservoirs. Numerical simulations were conducted to investigate the dissociation and reformation behaviors of methane hydrate during depressurization and shut-in periods. A high gas production rate was obtained for a few years after primary depressurization; however, the production rate drastically decreased because the sensible heat of the reservoir was exhausted owing to hydrate dissociation. During the shut-in period after 10 years of production, methane hydrate continued to dissociate owing to the geothermal heat flow for a few decades and then started to reform in accordance with pressure recovery. Case studies with shut-in periods of 10–30 years showed that 20 years of shut-in was the most effective period before the next depressurization. A conceptual operation plan for a hypothetical field showed that the production time increased to 120 years from 70 years when the cyclic depressurization method was considered. The recovery factor increased from 42.4% to 71.5%. The number of operating wells was reduced to less than one-third compared with the operation with normal depressurization method only. The results suggest that the cyclic depressurization method is a sustainable heat supply method driven by the geothermal heat flow and is both economically and environmentally sound.

1. Introduction

Gas hydrates are crystalline solids comprising water and gas [1]. Methane hydrate, the main gas hydrate in nature, is stable under appropriate temperature and pressure conditions and is generally observed in permafrost and deepwater environments. Methane hydrate is considered an unconventional gas resource of the future [2]. Because of the high demand for energy, energy-importing countries such as Japan, China, India, and South Korea are seeking to explore and exploit methane hydrate. Methane hydrate-bearing sandy sediments were found in the continental margins of Japan, South Korea, India, and USA [3–6]. Oceanic methane hydrates in sandy sediments as well as methane hydrates trapped in permafrost are primary targets for gas production [7,8].

At present, commercial gas production from methane hydrate reservoirs has not been achieved; however, a few successful flow tests have been performed in arctic and oceanic environments. The only gas production example in oceanic environment is that in the eastern Nankai Trough during March 12–18, 2013, as part of a program sponsored by the Research Consortium for Methane Hydrate Resources in Japan (MH21 Research Consortium) [9]. In this case, gas was produced for six days by the depressurization method. In arctic regions such as the Mackenzie Delta, Northwest Territories, Canada, and the Alaska North Slope, USA, gas production tests from sandy reservoirs were performed by the well heating method, the depressurization method, and the N_2–CO_2 injection method [10–13]. In addition, as a result of a chance event, the field performance observed in the Messoyakha gas field of East Siberia is considered the first gas production from a hydrate-bearing reservoir by the depressurization method [14,15]. The abovementioned field tests suggest that depressurization is a promising gas production method for sandy reservoirs.

Depressurization is a gas production method that dissociates methane hydrate by decreasing the pressure in the wellbore drilled through hydrate-bearing sediments. Methane hydrate becomes thermodynamically unstable with decreasing pressure and

* Corresponding authors.
E-mail addresses: yoshihiro-konno@aist.go.jp (Y. Konno), jiro.nagao@aist.go.jp (J. Nagao).

http://dx.doi.org/10.1016/j.enconman.2015.11.030
0196-8904/

dissociates owing to the sensible heat of the sediments and the geothermal heat flow. The geological requirements for this method are high permeability, high temperature, and high geothermal heat fluxes. Past experimental and numerical studies have shown that the recovery factor depends on the initial temperature of the reservoir when the initial permeability is higher than a threshold value [16,17]. In addition, a numerical analysis of dimensionless parameters showed that the most dominant parameters are the dimensionless initial temperature of the hydrate reservoir and the dimensionless phase equilibrium pressure of gas hydrate [18]. It indicates that the consumed energy for hydrate dissociation comes from the energy contained in formation [18]. Moreover, the driving force for hydrate dissociation is very important in hydrate dissociation by depressurization [18]. Although the geothermal heat flow contributes to the hydrate dissociation, the gas production rate decreases after the sensible heat is exhausted. Thus, gas production lasts until the sensible heat is consumed [17]. The inferred recovery factor is approximately 40% when using the normal depressurization method because much methane hydrate remains in the reservoir owing to the lack of dissociation heat [16,17].

Heat supply is required to increase the recovery factor of methane hydrate. Thermal stimulations (e.g. hot water injection and well heating) and hydrate-former gas (e.g., CO_2) injection are proposed as heat supply methods to enhance methane hydrate dissociation [19–22]. Recently, intentional ice formation by decreasing the production pressure below the quadruple point was presented as a new source of heat supply [17,23]. These methods are called enhanced methane hydrate recovery (EMHR) and assist the primary recovery by the depressurization method. However, the thermal stimulation method is quite expensive [24]. The feasibility of EMHR, which depends on the energy profit ratio and additional development cost, will be studied in the future.

To achieve commercial gas production from methane hydrate reservoirs, a long-term development strategy has to be established. In particular, enhancing the recovery factor is a major challenge that needs to be solved. In this study, the cyclic depressurization method, a new production concept relative to the common EMHR, is presented as a management scheme for sustainable gas production. The cyclic depressurization method alternates depressurization and shut-in periods until all methane hydrate is dissociated by the geothermal heat flow. As mentioned above, the gas production rate driven by geothermal heat flow is too low to meet the requirement of economical gas production. Thus, in this method, appropriate shut-in periods are set until the reservoir temperature recovers and supplies the sensible heat to realize economical gas production rates. To investigate the appropriate shut-in periods, we performed numerical reservoir simulations. After the primary depressurization, the hydrate dissociation and reformation behavior during the shut-in periods were analyzed. Based on the analysis, the average production rate and recovery factor by cyclic depressurization were evaluated for various shut-in periods. Finally, the feasibility of the cyclic depressurization method is discussed by considering the conceptual operation plan of a hypothetical field and the appropriate shut-in period.

2. Method

2.1. Reservoir simulation

The numerical reservoir simulator MH21-HYDRES was used to predict the hydrate dissociation, reformation, and production behavior. MH21-HYDRES is a compositional reservoir simulator developed by the University of Tokyo, Japan Oil Engineering Ltd., and the National Institute of Advanced Industrial Science and Technology under the MH21 Research Consortium to study the gas productivity of methane hydrate reservoirs [25,26]. Mass and heat balance equations are solved with various component models such as hydrate dissociation and formation. Kinetic models are used to describe the hydrate dissociation and formation behaviors. The theory behind the various models are described in detail in our previous papers [16]. MH21-HYDRES was used to analyze the results of laboratory experiments and the field tests [23,27–30]. Through comparative studies and history-matching simulations, the applicability of MH21-HYDRES was confirmed. In addition, MH21-HYDRES was recognized as a leading hydrate reservoir simulator through a collaborative, international effort to compare five distinct methane hydrate reservoir simulators [31].

2.2. Initial and boundary conditions of the reservoir model

Fig. 1 shows a schematic of the reservoir model. The cylindrical coordinate system was used to model the methane hydrate layer with overburden and underburden of clay and water. The drainage radius was 250 m. The model in the radial direction was discretized into 95 grids increasing logarithmically from 0.012766831 m. The methane hydrate layer was modeled as a homogeneous 50-m-thick layer. Each grid size of the hydrate layer was 0.5 m in the vertical direction. The thickness of the overburden and underburden was 300 m and 800 m, respectively. The overburden in the vertical direction was discretized into 100 grids increasing logarithmically from 0.5 m at the nearest grid of the hydrate layer. Although the discretization of the underburden was done in the same manner as the overburden for 300 m from the hydrate layer, an additional grid of 500 m was set at the deepest section as geothermal heat source. The porosity was 0.4 for all sediments. The hydrate saturation in the hydrate layer was 0.6. The sediments were fully saturated with water. The water column was set above the overburden to simulate water flow from the sea bottom. By using large porosity for the grid of the water column, we modeled the water source for 100 years and almost constant pressure. The water depth was 1000 m. All outer boundaries have no mass and heat flows. The initial pressure was the hydrostatic pressure of 3.5% saline water. The initial temperature was calculated by the constant geothermal gradient of 0.03 K/m with constant sea-bottom temperature of 3.5 °C. All model parameter are summarized in Table 1.

2.3. Production and shut-in operation

A single vertical well system was assumed. The radius of the production well was 0.1 m. The 50-m-thick hydrate layer was completely perforated. The basic simulation case was that of production for 10 years with a shut-in period of 90 years. Subsequently, the production behavior as a function of primary depressurization, hydrate dissociation, and reformation during the shut-in period were analyzed. To investigate the appropriate shut-in period for the cyclic depressurization method during the 100 years of operation time, case studies of variable shut-in periods between 10 and 30 years were conducted. A production period of 10 years was simulated after every shut-in period. The total operation time was 100 years. Thus, we conducted five, four, and three periods of production for shut-in periods of 10, 20, and 30 years, respectively. The production pressure was 3.0 MPa in all cases.

3. Results and discussion

3.1. Primary depressurization

Fig. 2 shows the gas production rate and recovery factor during primary depressurization. The gas production rate increased with time owing to the expansion of the hydrate dissociation zone;