Energy 160 (2018) 835–844

Contents lists available at ScienceDirect

Energy

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

Pilot-scale experimental evaluation of gas recovery from methane hydrate using cycling-depressurization scheme

Yi Wang [a, b, c], Jing-Chun Feng [d, e], Xiao-Sen Li [a, b, c, *], Lei Zhan [a, b, c, f], Xiao-Yan Li [a, b, c, f]

[a] Key Laboratory of Gas Hydrate, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, Guangzhou, 510640, PR China
[b] Guangzhou Center for Gas Hydrate Research, Chinese Academy of Sciences, Guangzhou, 510640, PR China
[c] Guangdong Province Key Laboratory of New and Renewable Energy Research and Development, Guangzhou, 510640, PR China
[d] School of Enringing, Sun Yat-sen University, Guangzhou, 510275, PR China
[e] Guangdong Research Center for Climate Change, Guangzhou, 510275, PR China
[f] University of Chinese Academy of Sciences, Beijing, 100049, PR China

ARTICLE INFO

Article history:
Received 16 May 2018
Received in revised form
5 July 2018
Accepted 9 July 2018
Available online 17 July 2018

Keywords:
Hydrate decomposition
Cycling-depressurization
Pilot-scale
Experiment
Heat transfer

ABSTRACT

Methane hydrate is considered as a potential source of methane for energy supply. Therefore, developing approaches for enhancing gas recovery from hydrate reservoir is attracting extensive attention. The Pilot-Scale Hydrate Simulator (PHS), with an inner volume of 117.8 L, was applied to investigate gas recovery approach from hydrate reservoir. A novel cycling depressurization was carried out to improve the production efficiency of depressurization method. Three different schemes for gas recovery from hydrate reservoir were performed in the PHS, which were the Regular Depressurization (RD), the Semi-Cycling Depressurization (Semi-CD), and the Cycling Depressurization (CD), respectively. The production behaviors and heat transfer characteristics during hydrate dissociation in sandy sediments by different methods were compared and investigated. The advantages of the novel cycling depressurization were analyzed. The experimental results indicate that the effective average gas production rate in the experiments by CD is 17 times larger than that by RD. The energy cost per volume of gas production by the CD scheme can be significantly reduced by comparing with the RD scheme. Therefore, the production efficiency can be strongly enhanced by using cycling depressurization method. If the hydrate is dissociated by RD, the heat transfer is strongly coupled with the hydrate dissociation. However, if the hydrate is dissociated by Semi-CD or CD, the coupling of heat transfer and hydrate dissociation may be changed. During the well closing stage in the Semi-CD or CD scheme, the lower fluids flow rate in pores leads to a lower heat transfer rate, which leads to a lower hydrate dissociation rate in well closing stage.

1. Introduction

Methane hydrate is a naturally-occurring clathrate, in which a host lattice of water encloses guest molecules of methane. The guest molecules are not chemically bound to the water molecules, but are trapped in crystalline lattice. The resulting substance looks remarkably like ice, but it does not behave like ice. When methane hydrate is exposed to pressure and temperature conditions outside those where it is stable, the solid crystalline lattice turns to liquid water, and the enclosed methane molecules are released as gas. When dissociated at standard temperature and pressure, one volume of solid methane hydrate can release about 164 vol of methane gas [1]. Therefore, methane hydrate is also called as “flammable ice”.

Methane hydrate is known to occur in both onshore and offshore environments all over the world. Onshore deposits have been found in polar regions, hosted in sediments within and beneath permafrost. Marine occurrences have been found mainly in sediments of the continental margins [2,3]. These are the natural settings where methane and water are present, and where pressure and temperature conditions are suitable to form and sustain hydrate.

Within the framework of sustainable development, energy supply and energy security are important factors for both the developed countries and developing countries. Natural gas hydrate can be regarded as alternative energy source in future due to huge

---

[*] Corresponding author. Key Laboratory of Gas Hydrate, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, Guangzhou, 510640, PR China.
E-mail address: lixs@ms.giec.ac.cn (X.-S. Li).

https://doi.org/10.1016/j.energy.2018.07.054
0360-5442/© 2018 Published by Elsevier Ltd.

reserves of methane gas trapped in hydrate bearing formations. Although the precise estimation of methane hydrate all over the world is uncertain and the estimation vary from 2.8×10^{15} to 8.0×10^{18} m^3 [4,5]. The gas reserves in gas hydrate is considered as huge. The common perception can be expressed that gas hydrates contain most of the methane on earth and account for roughly a third of the mobile organic carbon all over the world [6]. Growing energy demands has brought increased attention to the potentially immense quantity of methane held in natural gas hydrates, which leads to a significant acceleration of the investigation of gas hydrates over the past two decades.

Over the past few decades, depressurization [7–9], thermal stimulation [10,11], chemical injection [12,13], and the combined application have been applied and investigated for hydrate destabilization [14–16]. The models of hydrate dissociation using different methods have been reported [17,18]. In order to observe hydrate dissociation in the real environment and assess the feasibility of exploitation technologies for commercial production, a series of field production tests on hydrate reservoirs have been carried out. The field test in the Mallik region of Canada in 2008 proved that gas production from hydrate accumulations was technically feasible from a sand-dominated reservoir, which promotes the potential of hydrates to be considered as an important recoverable energy resource [19]. During a field test in the north slope of Alaska by USA, the natural gas exchange by CO_2 injection into a methane hydrate reservoir has been tested for the first time [20]. Not only hydrate field tests of gas production from hydrate accumulations in the permafrost regions, but also the marine hydrate field tests were successfully conducted by Japan in the Nankai Trough in 2013 [21] and by China in the Shenhu area of South China Sea in 2017 [22]. In both of these marine hydrate field tests, the depressurization method is applied for gas recovery.

Because field-scale hydrate production tests are associated with the features of long-time preparation, huge cost and high risk, limited field tests can be applied in nature. Experimental investigations play significant role for researching and developing key exploitation technologies and clarifying the corresponding principals. A 5.8 L cubic hydrate simulator was employed for three dimension analyses of hydrate dissociation behaviors [23,24] and thermodynamic parameter optimization [25]. Pang et al. used a middle-sized reactor (10 L) to study gas hydrate decomposition with thermal simulation, and reported that the hydrate dissociation rate in closed reactor is mainly controlled by the heat transfer rate [26]. Fitzgerald applied a reactor (59.3 L) to investigate performance of methane hydrate decomposition by thermal stimulation. Their research showed a higher initial hydrate saturations may be beneficial to hydrate dissociation performance and larger heating rates caused higher efficiency [27]. Because the reservoir scale influences the fluid flow and heat transfer in the hydrate reservoir, several large reactors have been built in several laboratories recently. For example, Li et al. [28] have fabricated a 117.8 L hydrate simulator. They have adopted this simulator to develop approach for gas production from hydrate reservoirs [29,30], heat transfer and mass transfer characteristics [30], influence of well configuration [31], and entropy production features [32]. Funded by the German national research project SUGAR, hydrate dissociation experiment was executed successful in a 425 L large reactor [13]. Afterwards, an inter volume of 1710 L hydrate simulator, named as the High-pressure Giant Unit for Methane-hydrate Analyses (HiGUMA), was established in Japan. Hydrate dissociation experiments under one step and multi-step depressurization have been performed in this simulator, and the results indicated that an appropriate heat supplying scheme can enhance hydrate dissociation by depressurization [33].

According to the laboratory studies and field programs, depressurization method has been considered as the most cost-effective and practical way to dissociate gas hydrates [2]. Because the hydrate dissociation is an endothermic (heat absorbing) process, the dissociation-inducing depressurization leads to the decrease of reservoir temperature [34,35]. However, when the reservoir temperature decreases to the hydrate stability temperature at the production pressure, no more sensible heat in the sediment can be absorbed for hydrate dissociation. Afterwards, the heat consumption for hydrate dissociation is supplied by heat transfer from surroundings. Thus, the rates of hydrate dissociation decrease obviously. This phenomenon has been investigated experimentally [17] and also found in field test at the Shenhu area in South China Sea [22]. Therefore, serials of schemes are developed to enhance production efficiency during hydrate dissociation of depressurization. For example, step-depressurization [36], deep depressurization [30], and depressurization combined with heat stimulation [12] are carried out and investigated. During hydrate dissociation by step-depressurization, the reservoir pressure decreases step by step, and the recovery of hydrate can be enhanced by each step of depressurization. However, the low dissociation rate after depressurization is still not avoided. During hydrate decomposition by deep depressurization, the reservoir pressure drops below quadruple point of hydrate, and dissociation rate of hydrate can be obviously enhanced due to the heat releasing from ice formation. However, the generated ice in pore may cause the reduce of the permeability in sediment. During hydrate decomposition by depressurization combined with heat stimulation, the hot water is injected into reservoir to supply the phase change heat for hydrate and effectively enhances the hydrate dissociation. However, the additional energy cost also leads to the decrease of production energy efficiency.

By summarizing our previous research, a novel cycling depressurization is carried out to improve the production efficiency of depressurization method. During regular depressurization, the production pressure keeps stable after pressure-dropping stage, and the gas production rate in this stage decreases obviously. However, during cycling depressurization procedure, after pressure-dropping stage, the production well will be shut for a certain time for the recoveries of pressure and temperature. In this work, the Pilot-Scale Hydrate Simulator (PHS), with an inner volume of 117.8 L, was applied to investigate gas recovery approach from hydrate reservoir. In order to evaluate the influence of cycling-depressurization on hydrate dissociation, three different schemes for gas recovery from hydrate reservoir were performed in the PHS, which were the Regular Depressurization (RD), the Semi-Cycling Depressurization (Semi-CD), and the Cycling Depressurization (CD), respectively. The production behaviors and heat transfer characteristics during hydrate dissociation in sandy sediments by different methods were compared and investigated. The advantages of the novel cycling depressurization were analyzed.

2. Experiments

2.1. Experimental apparatus

Experimental system consists of 6 primary subsystems: (A) a stainless steel high-pressure reactor is the core component; (B) an injection system including the gas pump, the gas flow meter, and the metering pump for water; (C) a production control system which comprises the gas/liquid separator, the back-pressure regulator, the gas flow meter and balance; (D) an ambient temperature controlling system; (E) a data acquisition system collecting the experimental data of pressure, temperature as well as gas and water flow parameters, and (F) measuring units. The experimental system schematic is given in Fig. 1. The experimental system has