Applied Energy 112 (2013) 83–92

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

A three-dimensional study on methane hydrate decomposition with different methods using five-spot well

Yi Wang [a,b,c], Xiao-Sen Li [a,b,*], Gang Li [a,b], Yu Zhang [a,b], Bo Li [a,b,c], Jing-Chun Feng [a,b,c]

[a] Key Laboratory of Renewable Energy and 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] University of Chinese Academy of Sciences, Beijing 100083, PR China

HIGHLIGHTS

- The production behaviors of methane hydrate are obtained in the 3-D simulator.
- The different methods with a five-spot well are used for hydrate production.
- The water and gas production, efficiency, recovery, production rate are analyzed.
- The heat stimulation in conjunction with depressurization is the optimal method.

ARTICLE INFO

Article history:
Received 8 March 2013
Received in revised form 4 May 2013
Accepted 30 May 2013
Available online 26 June 2013

Keywords:
Methane hydrate
Three-dimensional
Thermal stimulation
Depressurization
Five-spot well

ABSTRACT

The cubic hydrate simulator (CHS) is used to study the methane hydrate production behaviors in porous media with three different methods, which are the depressurization (DP) using a single well, the heat stimulation using five-spot well (HS-5S), and the heat stimulation in conjunction with depressurization using five-spot well (H&D-5S), respectively. During these experiments, the initial hydrate saturations are all 35%; environmental temperatures are all 281.15 K; and the production pressures are ranged from 4.7 MPa to 7.4 MPa. The injection temperature (T_{inj}) and the rate of hot water injection (R_{inj}) in the experiments with the HS-5S and H&D-5S methods are 10 ml/min and 160 °C, respectively. The analysis of hydrate decomposition shows that almost all of the hydrate can be decomposed in the hydrate reservoirs with the above methods. The H&D-5S method, which can obtain the largest volume of gas production, the highest gas production rate, and the shortest production time, is the optimal method for hydrate production in this work.

1. Introduction

Gas hydrates are crystalline solids composed of water and gas molecules, especially methane, formed from the reaction under a relatively low temperature and high pressure [1]. A large amount of methane gas is trapped in natural gas hydrate reservoirs, and one volume of natural gas hydrate can release 160–180 volumes of natural gas at standard condition. Natural gas hydrates are distributed all over the earth in both the permafrost regions and ocean sediments of continental margins. The global resource of natural gas in hydrate deposits is estimated to be about 20,000 trillion m^3, and is considered as a potential energy source [2–4].

Methods for recovering natural gas from hydrates are various and are still developing. The most practical methods are the thermal stimulation method [5–7], the depressurization method [8–10], and the chemical inhibitor injection method [11]. In addition, a recent method for hydrate production is CO_2 replacement [12]. In this method, liquid CO_2 is injected into hydrate reservoirs to replace the methane gas.

Till now, the experimental investigations and field tests on methane hydrate production under varied methods have been carried out around the world [13]. The experimental studies of the hydrate dissociation by different methods in porous media using 1-D [6,14], 2-D [15], and 3-D [16–19] apparatuses have been reported. Meanwhile, field tests in the Mallik 2002 well demonstrate that the depressurization and the thermal stimulation methods for exploiting hydrates are viable [20].

Hydrate dissociation is a complex process that occurs during heat and mass transfer with dissociation kinetics of hydrate. The controlling regimes of hydrate production are considered as: the heat transfer method, mass transfer, and dissociation kinetic. The kinetics of the hydrate dissociation can be written as [21–24]

* Corresponding author at: Key Laboratory of Renewable Energy and Gas Hydrate, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, Guangzhou 510640, PR China. Tel.: +86 20 87057037; fax: +86 20 87034664.
E-mail address: lixs@ms.giec.ac.cn (X.-S. Li).

0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.05.079

$r^m = kA_s(f - f_{eq})$

where r^m (mol/m^3 s) is the consumption rate of methane; k (mol/m^2 Pa s) is the kinetic constant of hydrate formation or dissociation; A_s (m^2/m^3) is the reaction surface area, which is essentially the interface area between hydrate particles and the surrounding phases; f (Pa) is the fugacity of methane; f_{eq} is the methane fugacity at the equilibrium pressure corresponding to the local temperature.

Five-spot well system which is one of the multi-well systems has been used in the oil industry widely. From the geometrical symmetry of the developed five-spot pattern, it is possible to represent the whole system by a square section with an injection well in the center and four production wells in corners [25,26]. In the process of the gas hydrate production, hot water is injected into the center-well, and the gas and water in the hydrate reservoir are produced from the four production wells [27].

In this work, the three-dimensional cubic hydrate simulator (CHS) [8,16,17,28] were used to investigate the gas production behaviors of methane hydrate in porous media with different methods, which were depressurization using a single well, heat stimulation using five-spot well, and the heat stimulation in conjunction with depressurization using five-spot well. In these experiments, the initial hydrate saturations were 35%; and the environmental temperatures were 281.15 K. These conditions correspond to the conditions of the hydrate reservoir in the Shenhu area [29]. The production time, gas/water production, and efficiencies for production behavior with these methods and the effects of the depressurization and heat stimulation on the production behaviors were investigated.

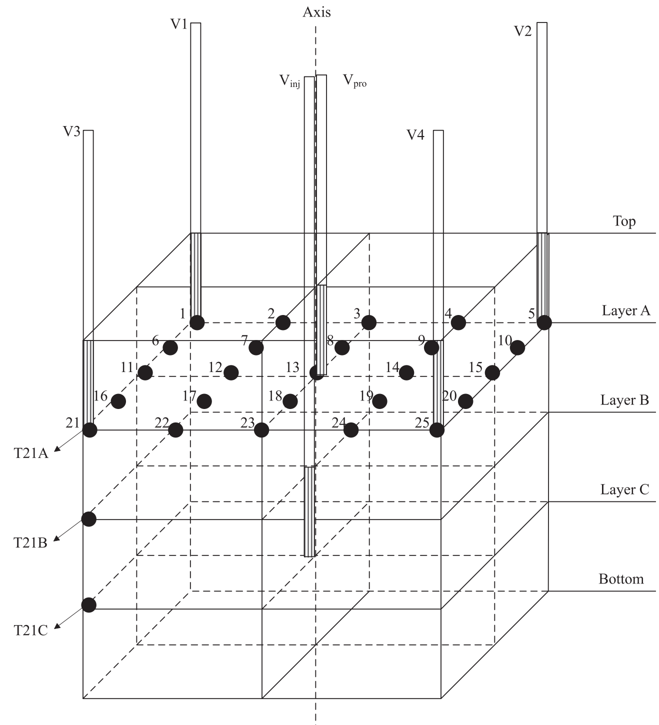

Fig. 2. Distributions of the thermocouples and wellheads within the CHS.

2. Experiment

2.1. Experimental apparatus

The details of the cubic hydrate simulator (CHS) have been reported in our previous work [8,28]. The schematic of the CHS [8] is shown in Fig. 1, which has been used to investigate methane hydrate production by huff and puff method [17] and depressurization method [8]. 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 measurement units. The high-pressure reactor (cubic inside, volume of 5.8 L, maximum pressure of 25 MPa) is the core component of the apparatus. The distributions of the thermocouples (measure temperatures) and wellheads within the CHS are shown in Fig. 2. As seen in Fig. 2, there are 25 × 3 thermocouples, two central vertical wells, and four vertical wells in the four corners of the CHS. There are three layers, which divide the measuring points and the wellheads, named: top (Layer A), middle (Layer B), and bottom (Layer C), respectively. In this work, during the process of heat injection, the inlet for the heat injection is the V_{inj} in the Layer C along the

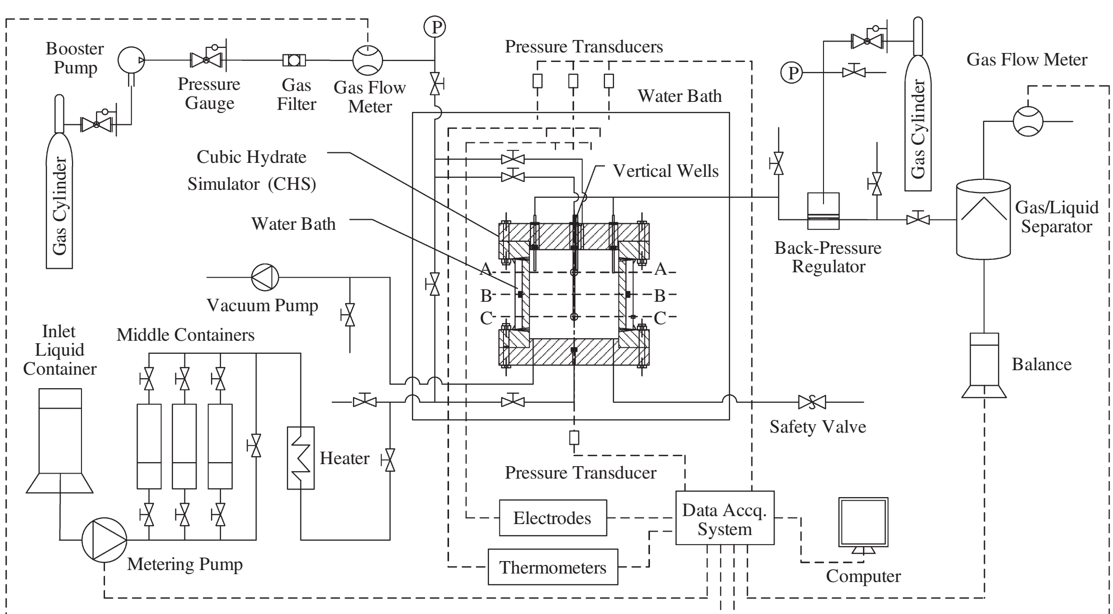

Fig. 1. Apparatus.