Chemical Engineering Science 163 (2017) 31–43

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Investigation on the dissociation flow of methane hydrate cores: Numerical modeling and experimental verification

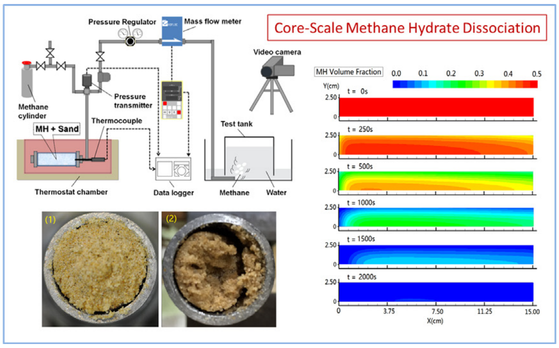
Lin Chen [a,b,*], Hikaru Yamada [c], Yuki Kanda [c], Junnosuke Okajima [a], Atsuki Komiya [a], Shigenao Maruyama [a]

[a] *Institute of Fluid Science, Tohoku University, Katahira 2-1-1, Aoba-ku, Sendai 980-8577, Japan*
[b] *Japan Society for the Promotion of Science (JSPS), Japan*
[c] *Graduate School of Engineering, Tohoku University, Aoba 6-6, Aramaki-aza, Aoba-ku, Sendai 980-8579, Japan*

HIGHLIGHTS

- Experiment on methane hydrate core is set-up and verified with numerical models.
- Dissociation characteristics of both non-porous core and porous core are compared.
- Heat transfer/permeability are critical for production enhancement.
- Scaling up from core to reservoir scale and challenges are discussed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 20 September 2016
Received in revised form 1 January 2017
Accepted 12 January 2017
Available online 14 January 2017

Keywords:
Methane hydrate
Dissociation flow
Porous media
Experiment
Production enhancement

ABSTRACT

Methane hydrate has become one of the important topics in recent years as there are more and more reports on possible actual production systems. The most challenging problem for stable methane hydrate production from sea beds or under permafrost regions lies in the complex flow and transportation process, which usually occurs inside the unconsolidated porous layers. The current study is focused on laboratory-scale explorations of the basic dissociation behaviors of methane hydrate. A high-pressure experimental system for the methane hydrate synthesis and dissociation process has been established in this study. The experimental system is specially designed to form and store the methane hydrate under high pressure and low temperature conditions. The mixing of sand with the formed methane hydrate makes it possible to control the initial saturation for dissociation in the current study. A numerical simulation model for core-scale dissociation flow has also been set up, and good agreement with the experimental data was found. It is found that the dissociation on a core scale is more heat-transfer controlled. Through comparisons with previous experimental and numerical results, it is known that the operation strategy will significantly affect the dissociation parameter behaviors. The effects of the initial temperature and permeability on the dissociation process are also shown in this study. Future considerations of core-scale models and reservoir-scale production strategies are also discussed in detail.

1. Introduction

Methane hydrate (MH) is a new type of energy resource that exists in large quantities in permafrost regions and under the ocean (Sloan, 2003; Boswell, 2009). It generally exists in the solid

---

[*] Corresponding author at: Institute of Fluid Science, Tohoku University, Katahira 2-1-1, Aoba-ku, Sendai 980-8577, Japan.
E-mail address: chenlinpkucoe@gmail.com (L. Chen).

http://dx.doi.org/10.1016/j.ces.2017.01.032

state with molecular methane caged inside molecular water crystals, and it is being widely mined under the oceans (Chong et al., 2016; Chen et al., 2016a). In recent years, it has become possible to extract and utilize such energy resources with the development of reservoir technologies. The production of methane gas from methane hydrate involves the pseudo-chemical reaction shown in Eq. (1). Basically, a possible ice formation and melting process will accompany the production process (Eq. (2)) (Bai et al., 2007; Reagan et al., 2008; Phirani and Mohanty, 2009; Chen et al., 2016a, 2016b). For this dissociation reaction, it is estimated that 1 m^3 of methane hydrate (standard solid state) will be converted to 164 m^3 of CH_4 gas and approximately 0.8 m^3 of water under atmospheric temperature and pressure. It is estimated that the hydrate mine in the Nankai Trough can provide Japan a stable energy supply that will last more than ten years (MH21 Project, 2016), which is very promising for countries with high dependence on energy imports.

$$CH_4 \cdot 6H_2O_{(s)} \rightarrow CH_{4_{(g)}} + 6H_2O_{(l)} \quad \Delta H_{MH} > 0 \tag{1}$$

$$H_2O_{(l)} \leftrightarrow H_2O_{(s)} \quad \Delta H_{ICE} < 0 \tag{2}$$

However, the "fire from ice" model includes a complex dissociation process and multiphase flow inside reservoirs, which is much different from traditional oil reservoirs. There are several research projects around the world on methane hydrate extraction (Collett, 2002; Ruppel et al., 2011; Vedachalam et al., 2015). In addition to the long production tests in the Messoyakha gas field in Russia (Makogon et al., 2007), and the Mallik gas hydrate field in the Mackenzie Delta region in Canada (Dallimore and Collett, 2005; Yamamoto and Dallimore, 2008; Nandanwar et al., 2015), Japan has also made production tests in the Nankai Trough and obtained successful gas extraction for approximately six days, obtaining 13,000 m^3 of methane gas (JOGMEC, 2013). Indeed, the test in Japan was stopped by sand production from unconsolidated methane hydrate layers. Since the beginning of fiscal year 2016, Japan has started the MH21 research project Phase III, which is focused on production method verifications. The ultimate goal of Japan's R&D projects is to establish reliable production technologies and bring the status to the commercial production stage by the 2020s (MH21 Program-Phase III, 2016).

According to major reviews (Sloan, 2003; Song et al., 2015), the knowledge of methane hydrate dissociation and production from unconsolidated reservoirs is still far from satisfactory in its current state. Both the core analysis from actual drilling tests and lab-scale tests and simulations have been made around the world in recent years. Currently, systematic analysis and new proposals of utilization systems are not often seen (Makogon, 1997; Sloan, 2003; Chen et al., 2016a). Kawata et al. (2005) originally proposed an LNG-methane hydrate combined power generation system and estimated the power generation IIR (Internal Rate of Return) in fifty years to be approximately 10%. Later, Maruyama et al. (2012) proposed a more sophisticated system, which consists of a methane hydrate production system, an on-site gas turbine power generation system, a hot water (from waste heat) and CO_2 (power generation by product) injection system, and an electric transportation system (to onshore customers), as shown in Fig. 1. This system has both production design and Carbon Capture and Storage (CCS) process considerations, which may need further detailed system construction and optimization.

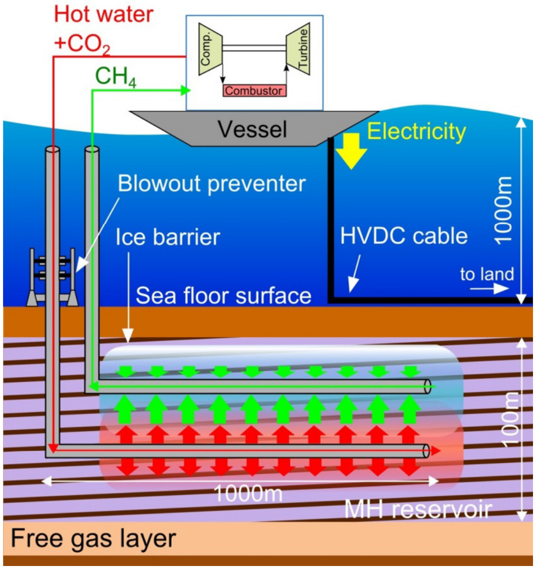


Fig. 1. Basic ocean methane hydrate reservoir and production model (with simultaneous CCS process) (Maruyama et al., 2012).

In recent years, although many programs and proposals have been put forward and tested for a couple of years, there still exist several major challenges for methane gas production from methane hydrate reservoirs: (1) as the methane hydrate reservoirs are usually in permafrost or undersea regions, especially undersea regions where dominant turbid layers exist and lead to many complex geological behaviors, the conditions of mature petroleum reservoir technologies and apparatuses are not applicable for methane hydrate reservoirs (Chen et al., 2016c; Yamada et al., 2016); (2) the fundamental mechanisms of the methane hydrate dissociation process are still not clear; the classical Kim-Bishnoi's model (Kim et al., 1987; Clarke and Bishnoi, 2000, 2001) is not applicable to various cases (Walsh et al., 2009; Windmeier and Oellrich, 2013; Kanda et al., 2016); (3) complexities of multiphase reactive flow inside porous media, aggressive depressurization processes and thermal considerations under low thermal conductivity reservoir conditions, and production behaviors and the skin-effect or "MH lensing" (Moridis and Reagan, 2007; Reagan et al., 2008); (4) very many technical problems such as flow control, sand production, production enhancement techniques, reformation of bearing layers, environmental issues, economic models, storage and utilization.

The technological challenges and research reviews of recent developments in studies of methane hydrates can be found in major articles in the literature (Song et al., 2015; Chong et al., 2016; Chen et al., 2016b). The equilibrium curves and production methods are plotted in Fig. 2. Depressurization, thermal stimulation and inhibitor injection are three basic ways to extract

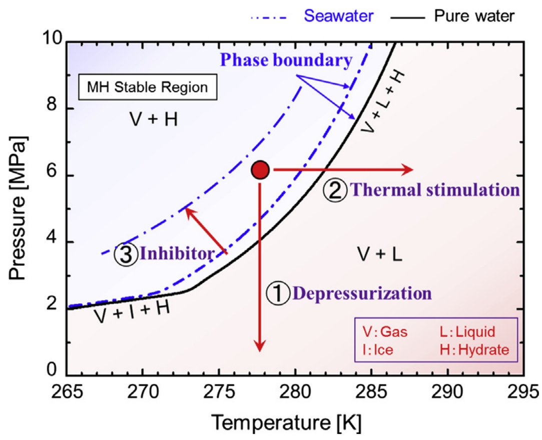


Fig. 2. Methane hydrate stability curve and representative production methods.