Study of methane hydrate as a future energy resource: low emission extraction and power generation

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Abstract. With the fast increase of world energy consumption in recent years, new and sustainable energy sources are becoming more and more important. Methane Hydrate is one promising candidate for the future energy supply of humankind, due to its vast existence in permafrost regions and near-coast seabed. This study is focused on the effective low emission utilization of methane hydrate from deep seabed. The Nankai Trough of Japan is taken as the target region in this study for methane hydrate extraction and utilization system design. Low emission system and power generation system with CCS (Carbon Capture and Sequestration) processes are proposed and analyzed for production rate and electricity generation efficiency problem study. It is found that the gas production price can reach the current domestic natural gas supply price level if the production rate can be improved. The optimized system is estimated to have power efficiency about 35%. In addition, current development and analysis from micro-to-macro scale methane hydrate production and dissociation dynamics are also discussed in detail in this study.

1. Introduction

Methane hydrate (MH), a substantial energy resource with vast existence in permafrost regions and under seabed, has been proved to be of high energy density and extractable in the near future [1-3]. Indeed, it has been reported that the overall gas hydrate reservoirs on earth contain around $2.0 \times 10^{14} \, \text{m}^3$ to $1.2 \times 10^{17} \, \text{m}^3$ of methane gas (STP). This ‘fire from underground’ is believed to harbor more than twice the amount of known fossil fuels on earth according to reports from geologists [4]. The exploring and production of methane gas from methane hydrate reservoirs have attracted major concerns of both the public and scientific communities in recent years.

Many countries have started methane hydrate Research and Development programs to test the feasibility of extraction technologies. The world first tests were in Russia in Messoyakha, which has become the only commercialized methane hydration production site since 1969 [4]. Canada put its
research production site at Mallik of Mackenzie Delta region since 1970 and tried thermal method production (Mallik 2002 test) and depressurization method (Mallik 2007 test) \cite{5}. For oceanic methane hydrate exploration, Japan has tried the assessment and production tests in Nankai Trough and obtained successful gas production around 6 days and obtained $1.3 \times 10^4 \text{ m}^3$ methane gas (see Figure 1; \cite{6}). In addition, China, Korea, India and other countries have also made small scale explorations and production tests in recent years.

Figure 1. Methane hydrate existence and production test in Japan \cite{6}.

For the situation of Japan, the first series research projects were started around 1992-1995, when the fundamental investigations of methane hydrate were proposed by Industrial Technology Research Institute (now called AIST: National Institute of Advanced Industrial Science and Technology). The first production experiment using hot water circulation method was made in 2002. Then a lot of real explorations and tests are executed in Nankai Trough of Japan, such as the geological survey in 2004, the proving test of depressurization method experiment in 2008, Nankai Trough real production test in 2012 and new round of test since May of 2016.

Those above projects and trials have made major progress in the production analysis and environmental assessment. However, there still exist several bottlenecks of real large scale commercialized and safe supply with methane gas. It is estimated by Sloan \cite{2} that only the production rate is higher than $5 \times 10^5 \text{ m}^3$ (STP) per day can the method be considered as economically reasonable. Also, due to the various conditions of widely spread methane hydrate reservoirs, there is no generally applicable method for stable production. According to major reviewers \cite{1-4}, the knowledge of methane hydrate dissociation and production from underground or below the sea bed are still not sufficient in the current stage.

In this study, a new low emission extraction and utilization system is proposed and analyzed for the feasibility and system power generation efficiency. The basic system construction, generation system and efficiency dependence on input parameters are discussed. Also the detailed analysis and investigations into the multi-scale methane hydrate dissociation dynamics are also introduced in this paper.

2. Low emission utilization system development

The basic dissociation and extraction process of methane gas from methane hydrate reservoirs is shown in Figure 2. According to the phase equilibrium curve in Figure 2(a), there are several ways of extracting methane gas from methane hydrate: increase the temperature (thermal stimulation), reduce the pressure (depressurization), adding inhibits or combined method of those. The dissociation reaction is expressed in Equation (1) under reservoir conditions.

$$CH_4 \cdot 5.75H_2O(s) \rightarrow CH_4(g) + 5.75H_2O(l) \quad \Delta H_{\text{diss}} > 0$$

(1)
Due to the high pressure and low temperature existence condition of methane hydrate existence in reservoirs, especially for undersea reservoirs taking the form of alternating sand and mud layers, it is very difficult to systematically extract and store the methane gas for possible commercial use.

Figure 2. Basic Methane Hydrate dissociation process, phase diagram and methods [7].

In the current stage, systematic analysis and novel designs of utilization systems are yet to be proposed [2, 4]. Kawata et al. [8], Maruyama et al. [9], Chong et al. [3] proposed several representative systems. That is not only for an energy-balanced model (thermal consideration), but also for a more practical way of CO$_2$ utilization/processing, by CCS or by a consideration of CO$_2$-hydrate replacement of CH$_4$-hydrate [3, 9]. It is usually concluded difficult for single numerical modeling to cover the complex thermal, fluid dynamic and mechanical changes of reservoir conditions [3].

Figure 3. Representative methane hydrate utilization system (with simultaneous CCS process) [9].

In this study, the detailed development and analysis of utilization and power generation model is discussed, which consists of production process, on spot gas turbine power generation, hot water and...
CO₂ re-injection, and electric transportation systems, as shown in Figure 3. Such system combines production estimation and CCS process, which may be one future trend of efficient utilization.

3. Low emission utilization system development

3.1. Macro-scale utilization system and challenges
For the proposed macro-scale utilization system, the production rate tests and relationship with the gas production price is conducted. Using the current systems and generation design, the electricity production will have different price levels, as shown in Figure 4. It can be seen from Figure 4 that in the current production rate (according to the test of Nankai Trough test in 2001), the price is much higher than the market price. And only when the production rate is improved to be around $8.0 \times 10^4$ m³/day the production would be compatible with the market price.

Figure 4. Methane gas production price estimation and comparisons.

![Figure 4](image-url)

Figure 5. Low emission system efficiency analysis. (a) CO₂ recovery rate; (b) system thermal efficiency.

![Figure 5](image-url)

(a) CO₂ recovery rate

(b) system thermal efficiency
Also in the current analysis, the CO\textsubscript{2} recovery rate and the efficiency of power generation are analyzed, as shown in Figure 5. It can be seen from Figure 5 (a) that when the recovery stage increase, the recovery rate will be increase. Also the increase of seawater injection would also lead to an increase of recovery rate. Indeed, the consideration of CO\textsubscript{2} recovery and re-injection would help increase the storage rate and substitute of the underground methane hydrate cages. The optimized system is estimated to be able to achieve power efficiency about 35% for the proposed system. The optimized system is estimated to be able to achieve power efficiency about 40% for the proposed system. However, as shown in Figure 5 (b), when the seawater injection is increased, the thermal efficiency would decrease, due to the increased pump power needed to do this. And an effective use of exhaust heat and water compressing heat would also increase the thermal efficiency.

3.2. Lab-scale experiments and tests
For the system efficiency improvement, the understanding of underground gas extraction and flow condition analysis is needed. In order to do that in lab environment, a core-scale experimental prototype is set up in this study, as shown in Figure 6. As it is very difficult to use the real core from real deep-sea methane hydrate reservoirs, in this analysis, the mimicking strategy of using water-ethanol inside porous sand is utilized to form the low permeability condition. The basic design is shown in Figure 6 (a) and by controlling of volume fraction of ethanol inside the porous sand, the formation of ice would be achieved and thus to generate the low permeability conditions needed. The permeability measurement results are shown in Figure 6 (b). This design is critical for the test of basic core characteristics and would be replaced by mixing of methane hydrate and sand easily to conduct real dissociation test in laboratory experiments [10-11].

3.3. Micro-scale mechanisms and visualizations
In this study, the concentration field near the reaction surface was visualized by using the phase-shifting interferometer system [12]. In this experiment, the MH dissociation phenomenon was observed in the reaction chamber shown in Figure 7 (a). Experiments were carried out in the temperature controlled room under the temperature condition of 2.0 °C. Temperature and pressure were set to about 5°C and 9.5 MPa after injection of methane gas. To observe the MH dissociation phenomenon pressure in the chamber was reduced by 0.1 MPa to below equilibrium pressure at 5 °C in the chamber. In the phase-shifting interferometer system, an arbaa prism was used as shown in Figure 7 (b). The arbaa prism splits an incident beam into four output beams with different
information. At the output of this prism, all three of the output beams are filtered by the polarizer to obtain three types of interference fringes.

![Figure 7. (a) chamber design](image)

**Figure 7. (a) chamber design**

![Figure 7. (b) phase-shifting interferometer](image)

**Figure 7. (b) phase-shifting interferometer**

![Figure 8. (a) Sequential phase-shifted data](image)

**Figure 8. (a) Sequential phase-shifted data**

![Figure 8. (b) Phase difference distribution of methane](image)

**Figure 8. (b) Phase difference distribution of methane**

To visualize the dissociation process of MH, the pressure in the chamber was depressurized below equilibrium pressure (about 4.1 MPa) [12]. The sequential phase-shifted data during MH dissociation process is shown in Figure 8(a). The phase difference distribution of methane in the gas phase during MH dissociation process is plotted in Figure 8(b). Changes of the phase difference in those figures indicate density variation due to heat and mass transfer near the solid-gas interface. In this experiment, it was found that unsteady density distribution of methane in the gas phase existed during MH dissociation processes and it is possible to test quantitatively of the interface dynamics of methane hydrate dissociation process.

3.4. Lab-scale production behaviors

Using the basic dissociation apparatus as discussed in Figure 6 (a), dissociation experiment is conducted. The basic dissociation process can be divided into three stages in core scale, as shown in Figure 9. The first stage is the quick temperature drop process due to the fast dissociation when the right end of the chamber is exposed to low pressure. As the dissociation reaction is endothermic kind, the temperature drops quickly. Then the heat use and boundary conduction from ambient reach a
balanced states for the long duration of core temperature region. After the dissociation is finished, the temperature will recovery to the ambient value. This result is important as to support the basic thermal analysis in large scale system extraction.

Figure 9. Basic core-scale dissociation parameter behaviors.

3.5. Core-scale numerical simulation and comparison
The basic high-pressure operating system of core-scale dissociation process in this study is simplified to be a 3D numerical model and with also an extension to three-dimensional model analysis in later discussions [13-14]. As shown in Figure 10, the physical model is a horizontally operated cylinder core, where an axis is applied for simplicity of model. The internal region of the model can be applied with porous media with artificial bearing layer porosity, permeability and other heat transfer/flow parameters [12, 14, 15-18].

Figure 10. (a) simplified 3-D core model

Figure 10. (b) temperature evolution of the core

Figure 10. Basic modeling and temperature results for low permeability dissociation case (porous case; adiabatic boundary; half view)
In the simulation, the model scale is set to be within a lab scale experimental core from $L = 10$–$30$ cm length and $D = 2.0$–$5.0$ cm diameter core. The numerical results are shown in Figure 10 (b) and Figure 11 for basic dissociation process and the ice formation. From Figure 10 (b) it can be seen that the basic dissociation process is delayed due to the low permeability in the core. Also the core-scale dissociation is governed by the boundary heat transfer conditions, as the dissociation curves are shaped by the boundary heat transfer conditions. In Figure 11, it can be seen that the ice forming dominant the dissociation core and resides in the bottom part due to gravity effect, leaving the methane gas in the upper part. This result agrees with experimental result, where the ice is found for the non-porous dissociation chamber, as shown in Figure 11 (b). However, the detailed effects of ice on the methane gas production, water flow and hydrate dissociation kinetics is still not well understood. The question still remains that how the local or gross thermal field conditions are will affect the global gas production, and how is the effect on core-scale? More studies/proposals are recommended for better understanding of those related phenomena and methods.

Figure 11. (a) ice volume fraction

Figure 11. (b) ice formation inside experimental core

Figure 11. Three dissociation (3D) model and real experimental core with ice formation.

4. Conclusion

In this study, the systematic analysis of a proposed methane hydrate extraction and power generation system is conducted. The Nankai Trough of Japan is taken as the target for methane hydrate extraction and utilization system design. Low emission system and power generation system with CCS (Carbon Capture and Sequestration) processes are proposed and analyzed. The optimized system is estimated to be able to achieve power efficiency about 35% for the proposed system. Detailed system analysis and dissociation dynamics studies are also included in this paper. It is hoped that the current study can be useful for related new energy and sustainability development of the industry.

Acknowledgement

The support from JST-CREST (Program: Breakthrough on Multi-scale Interfacial Transport Phenomena in Oceanic Methane Hydrate Reservoir and Application to Large-Scale Methane Production) and JSPS Overseas Researcher Grant (No. 16F16068) are gratefully acknowledged by the authors. The authors are grateful for the assistance of permeability experiments from Mr. Guillaume Lacaille (former graduate student of Tohoku University, Japan).

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