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Numerical analysis of core-scale methane hydrate dissociation dynamics and multiphase flow in porous media

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HIGHLIGHTS

- New core-scale multi-phase flow and dissociation reaction model is set-up and validated.
- Inclined dissociation front movement for case under gravity are identified and compared.
- Boundary thermal effect is found critical for core-scale dissociation behaviors.
- Ice formation is identified and discussed with the general production strategies.

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ABSTRACT

Methane hydrate is one of the most promising future energy resources for humankind. In recent years, due to its vast existence in permafrost regions and deep ocean beds, increasing attention has been paid to the extraction, transportation and utilization of methane hydrate. The current study proposed core-scale numerical investigation models for the complex multiphase dissociation flows of methane hydrate inside porous media, which is a continuation and an extension of previous numerical investigations. The current numerical model focuses on the depressurization process and thermal boundary effects and discusses the parametric effects of the core-scale internal flows and controlling factors of the dissociation boundaries. The new findings with respect to the dissociation front movement and water–ice equilibrium effects during the dissociation process are also analyzed in this study. Ice formation and boundary heat conduction limitations are found to be critical for the smooth production of methane gas. Based on these results, trade off and production strategies for depressurization methods and thermal stimulation methods are also discussed in detail. It is hoped that this study will be useful for related core-scale analysis and possible engineering system designs.

1. Introduction

Methane hydrate (MH) is a substantial energy resource with vast existence in permafrost regions and under the seabed. MH has also been shown to be one of the most promising fuels for humankind (Sloan, 2003; Boswell, 2009; Chong et al., 2016). It is referred to as 'fire from the underground' and is believed to harbor more than twice the amount of known fossil fuels on earth according to reports from geologists (Kvenvolden, 1993; Klauda and Sandler, 2005; Makogon, 2007; Lu, 2015). The exploration and production of methane gas from methane hydrate reservoirs have attracted major concerns from both the public and scientific communities in recent years.

In recent years, many countries have started research and development programs in methane hydrate exploration and production. The pioneering work began in Russia at Messoyakha, which began operation in 1969 and has become the only commercialized methane hydration production site using the depressurization method (Makogon et al., 2007). In cooperation with Japan, the United States and other industrial and research cooperators, Canada has also operated a research production site in

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the Mackenzie Delta region since the 1970s. For oceanic methane hydrate, Japan has attempted assessment and production tests in the Nankai Trough and achieved successful gas production for approximately 6 days and obtained $1.3 \times 10^4\ m^3$ of methane gas (JOGMEC, 2013). In addition, China, Korea, India and other countries have also made small-scale explorations and production tests in recent years.

These projects and trials have made major progress in terms of production analysis and environmental assessment. However, there still exist several bottlenecks in real large-scale commercialization and the safe supply of methane gas. Sloan (2003) estimated that only when the production rate exceeds 5×10^5 standard m^3/day can the method be economically reasonable. Additionally, due to the various conditions of widely spread methane hydrate reservoirs, there is no generally applicable method for stable production. According to major reviewers (Sloan, 2003; Makogon, 2007; Lu, 2015), knowledge concerning methane hydrate dissociation and production from the underground or below the sea bed are still not sufficient.

The basic dissociation and extraction processes of methane gas from methane hydrate reservoirs are shown in Fig. 1. According to the phase equilibrium curve in Fig. 1(a), there are several ways to extract methane gas from methane hydrate: increase the temperature (thermal stimulation), reduce the pressure (depressurization), or combinations of these methods. The basic reaction equation can be seen in Eq. (1). Eq. (2) shows the possible co-existence of water–ice phase equilibrium under reservoir conditions. The multiphase reacting flow situations are briefly shown in Fig. 1 (b). For this complex process, it is estimated that 1 m^3 of methane hydrate will dissociate to become 164 m^3 of methane gas and approximately 0.8 m^3 of liquid water under atmospheric temperature and pressure conditions (Kvenvolden, 1993). During the dissociation, the porosity and permeability of the porous media varies and interacts with the dynamics of the dissociation flow, as shown in Fig. 1(b).

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

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

Due to the high-pressure and low temperature conditions that exist in methane hydrate reservoirs, especially in under-sea reservoirs taking the form of alternating sand and mud layers, it is very difficult to systematically extract and store methane gas for possible commercial use. In the current stage, systematic analysis and novel designs of utilization systems have yet to be proposed (Makogon, 1997; Sloan, 1998). Kawata et al. (2005), Maruyama et al. (2012), and Chong et al. (2016) proposed several representative systems. For example, the Maruyama et al. (2012) model consists of the production process, on-the-spot gas turbine power generation, hot water and CO_2 re-injection, and electric transportation systems, as shown in Fig. 2. Such a system combines the production estimation and CCS process, which may be one future trend of efficient utilization.

Since the 1930s, methane hydrate has been found to be responsible for the blockage of flow pipelines in Arctic regions (Hammerschmidt, 1934), and research into MH formation and dissociation is still a primary topic (Yousif and Dunayevsky, 1997; Chong et al., 2016). Earlier representative studies also include the effect of methane gas leakage (from methane hydrate) on global warming (Englezos and Hatrikiriakos, 1994) and the thermodynamic and kinetic processes of methane hydrate dissociation (Holder et al., 1982; Vysniauskas and Bishnoi, 1983; Englezos and Bishnoi, 1988; Yousif et al., 1991; Masuda et al., 1999). Those studies mainly focused on the fundamental dissociation laws and thermodynamic analysis of the methane hydrate dissociation process. In recent years, many studies and reports have also been published on the production and bearing layer analysis of real reservoir data (Yousif et al., 1991; Masuda et al., 1999; Tsuji et al., 2004; Su et al., 2012).

Furthermore, due to the complex real reservoir conditions and the limitations of real-scale analysis, additional studies using lab-scale experimental and numerical analysis have been proposed. Representative studies are mainly focused on core scale analysis. For example, Yousif et al. (1991) established a core that was 15 cm long (with cross sectional area 11.4 cm^2) to test the dissociation behaviors, including the pressure change, dissociation location and so on. This is one pioneering core model for lab-scale core experiments. Masuda et al. (1999) conducted another experiment using Berea sandstone cores, and this work became the classic experimental core data that has been used in ensuing modeling and comparisons. Kneafsey et al. (2007) designed an experimental core (26.7 cm long with a 7.6-cm diameter) and used X-Ray CT to test the density field and dissociation process. Seol and Myshakin (2011) set up an experimental core that was 18.8 cm long (5.1-cm diameter), used a X-Ray CT measurement and compared the results with those of TOUGH + HYDRATE (Moridis et al., 2008). Li and Zhang (2011) reported an experimental and theoretical analysis of the methane hydrate dissociation kinetics at point greater than the quadruple-phase equilibrium and considered the core changes during that process, and good correlations with the measured data were obtained. Konno et al. (2015) performed experimental tests using core samples from Nankai Trough in Japan (with a 29-mm diameter) using artificial seawater through flows to test the permeability characteristics of the methane hydrate deposit, and a two to three orders of magnitude difference was found compared with traditional estimations.

As shown in Fig. 1(b) and Eq. (1), the basic reacting flow system includes at least three phases (gas, liquid, and solid) and four components (methane gas, water, porous sand structure, methane hydrate, or possibly ice). The endothermic nature of the reaction also brings more complexity to the system (possible heat transfer effects and possible ice formation inside the porous media). In early years, only gross models or one-dimensional (1-D) models were discussed (Yousif et al., 1991; Ahmadi et al., 2001). Later, several major research groups have developed numerical code for a partial simulation of the problem. Representative model set-ups and representative parameters from those studies are summarized and compared in Table 1. From those studies, discrepancies still exist for different results due to the problem complexity and diverse controlling factors of each specific case. Generally, in those models, the underground dissociation flow and methods are primarily derived from traditional gas/oil reservoir engineering where the heat transfer model and variable properties are not considered in detail. The relationship and indications from a core-scale model to real-scale reservoirs have yet to be verified (Kurihara et al., 2011; Nagao, 2012). For such a purpose, more sophisticated and precise methods and numerical analyses are still urgently required as to obtain a clearer picture of methane hydrate dissociation flows in porous media (Moridis et al., 2008; Gamwo and Liu, 2010).

The current study is a continuation and extension of the above-mentioned numerical investigations of the complex multiphase dissociation flows inside porous media. In this study, a careful numerical model is developed for two-dimensional (2-D) core-scale porous media flow with methane hydrate dissociation. As opposed to traditional models, the current numerical model focuses on the depressurization process and thermal boundary effects and discusses the parametric effects on the core-scale internal flows and on the controlling factors. New findings with respect to the dissociation front movement and water–ice equilibrium effects during the dissociation process are also analyzed in this study.