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Numerical study of gas production from methane hydrate deposits by depressurization at 274 K

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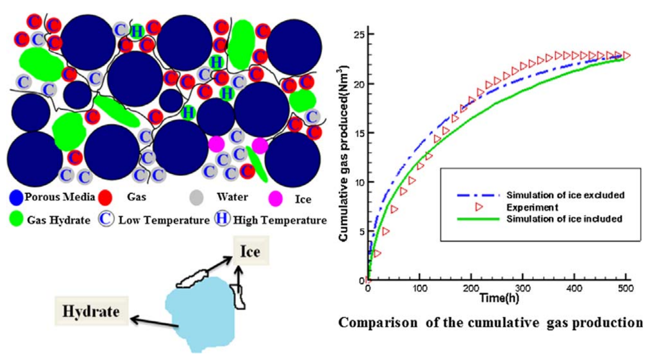
HIGHLIGHTS

- The characteristic of hydrate decomposition at 274 K was numerical analyzed.
- Ice generation during hydrate decomposition was investigated.
- The effect of ice generation and initial hydrate saturation on pressure, temperature, permeability was obtained.
- The influence factors and features of the cumulative gas production and the instantaneous gas generation rate are analyzed.

GRAPHICAL ABSTRACT

Schematic diagram illustrating the process of gas hydrate decomposition under a relatively low temperature and the form of the ice generating which adhere on the hydrate. The figure shows that the ice generating can make the instantaneous gas rate decline, but cannot changes the final gas production.



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ABSTRACT

As a potential new source of energy, gas hydrate has been the focus of research around the world. In this study, based on a summary of existing models, a one-dimensional mathematical model containing four phases (water, gas, hydrate, and ice phases) and three constituents (water, gas, hydrate) based on the finite difference method (FDM) was established for analysing methane hydrate decomposition at a relatively low temperature condition (approximately 274 K) by depressurization in porous media. This model can be used to investigate gas hydrate exploitation under a wider range of temperatures (e.g., deep seabed or permafrost conditions). When the initial temperature of the hydrate reservoir is approximately 274 K, ice generation occurs during exploitation. This investigation focused on the characteristics of hydrate decomposition, ice generation and ice distribution by changing the parameters of relevant settings. The analysis addressed the effects of ice generation on pressure, temperature, permeability, and cumulative gas production; the influence of other relevant parameters on each other; the influential factors and features of cumulative gas production and the instantaneous gas generation rate. The results showed that ice generation gradually increases during the hydrate decomposition process and occurs early and near the production well due to a large pressure gradient. As an unfavourable factor, ice generation causes the absolute permeability, instantaneous gas generation rate and local pressure to decline. The production well pressure is the determinant of ice generation. Moreover, the final cumulative gas production is

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determined by the hydrate characteristics, which include the hydrate saturation, reservoir porosity and permeability. Ice generation reduces the gas generation rate, but this does not affect the final cumulative gas production.

1. Introduction

Gas hydrate is a compound of gas molecules that are wrapped by the hydrogen bonds of water molecules onto a cage structure, and hydrate plays an important role in flow assurance, safety issues, energy recovery and climate change [1,2]. As a type of energy sources with great potential, gas hydrate has received considerable research attention in recent decades. The formation and decomposition of gas hydrate depend on the pressure, temperature, gas composition, salinity of the water, characteristics of the porous media and other factors. Hydrates remains stable at certain pressures and temperatures and achieves a balanced state [3].

Several methods are used for gas production (decomposition) from gas hydrate in the field, including depressurization, by decreasing the pressure of the system [4–6]; thermal stimulation, which involves hot water injection and increasing the temperature [7]; and a combination of depressurization and thermal stimulation [8,9]. In general, depressurization is considered the simplest and most promising method because of its effectiveness and the fast response of hydrate to pressure waves [10]. Several laboratory experiments used depressurization to recover gas hydrate, and showed that it is an effective gas production method. Several field tests, such as those at the Mallik site [11], North Slope of Alaska [12], Nankai Through along the Pacific coast of Japan [13], and in South China [14,15] have revealed that depressurization is the least energy intensive and most promising gas production method from the perspectives of energy efficiency and productivity. Three periods were defined during the depressurization process: free gas, mixed gas and gas production from hydrate decomposition [16]. Three major factors determine the depressurization-induced gas production rate: the kinetics of methane hydrate decomposition, gas flow through the reservoir, and heat transfer to the dissociating zone [17]. Several decomposition experiments have been conducted to investigate the influences of the temperature, pressure [18], concentration [19], salt level and injection rate [20]. However, several mechanisms of gas hydrate preservation may affect depressurization. These mechanisms include the methane hydrate self-preservation effect and reformation during the production of gas from hydrate deposits during depressurization.

The self-preservation effect was observed and described in early 1986. A surprisingly slow decomposition was observed during gas hydrate production in the Gulf of Mexico at an ambient pressure and $-20\,^{\circ}C$ [21]. Later, Yakushev and Istomin reported decomposition rates that were several orders of magnitude lower than the expected decomposition values, especially at low temperatures below the freezing point and at atmospheric pressure [22]. The low decomposition rates were attributed to the self-preservation effect. Generally, the self-preservation effect results in the extremely slow decomposition of gas when the external pressure decreases the three-phase equilibrium pressure of the gas-ice-hydrate system at subzero temperatures as a result of thin ice film emergence on the gas hydrate surface [23,24]. The self-preservation effect is critical for the feasibility of hydrate-based gas storage technology.

However, the mechanisms of the self-preservation effect remain poorly understood due to insufficient information describing the precise composition of the original hydrate, the common presence of large fractions of ice as a secondary phase, the unknown extent of decomposition and the alteration experienced during transport [25]. The self-preservation effect is enhanced by increasing pressure and decreasing temperature [23]. Recently, many studies related to hydrate decomposition have mainly focused on the dependence of self-preservation on ice formation at a temperature below 273 K and an ambient or moderate pressure [26–28]. At ambient pressure, unstable gas hydrates decompose rapidly to free gas and ice. The ice film exhibits fractal features and increases mass transfer resistance during the diffusion of methane from the hydrate region [23]. The ice film creates unexpected stability under non-equilibrium conditions and slows decomposition [29]. In contrast, experimental data collected using electron-microscopy revealed self-preserved (partly dissociated) methane hydrate particles that no evidence was found for ice-rind development around individual hydrate grains [30]. Additionally, the gas production rate was obviously enhanced around the freezing point [31]. Although the detailed mechanism remains unclear, ice formation plays an important role in hydrate decomposition. Hence, the energy efficiency remains questionable if gas hydrated decomposes at freezing point.

Considering the temporal and spatial limitations of monitoring during ice formation, numerical simulation has the advantage of being low cost and allowing for easy adjustment of the space and temporal scales. A single-phase model was proposed based on a conventional, adjacent, hidden, and step-down decomposition process; however, dynamic water flow conditions could not be simulated with this model [32]. A two-phase, three-dimensional variable composition model was developed to simulate decomposition and formation processes (involving water and any mixture of methane, ethane, or propane) and address fundamental questions regarding the feasibility of gas production schemes and the utilization of gas hydrate, an unconventional energy resource [33]. Then, a three-phase, multicomponent model that treats decomposition as a condition of methanol injection was developed [34]. An analytical model was presented to analyse the main factors that affect hydrate decomposition in porous media. Researchers found that the most important reservoir variable was the permeability of the ice region that formed during hydrate decomposition. Moreover, models that couple multiphase and multicomponent factors are necessary to analyse the effects of ice formation on gas hydrate decomposition.

The effects of ice formation are related to the decomposition kinetics of gas hydrate. The kinetic model (Kim-Bishnoi model) of hydrate decomposition was first proposed by Kim et al. [35]. The results revealed that the decomposition rate was proportional to the particle surface area and the difference in the fugacity of methane at the equilibrium pressure and decomposition pressure. In the kinetic model, the system is composed of heat and three mass components. Musuda et al. [17] developed a three-dimensional form of the hydrate decomposition kinetic model and used the model to simulate gas hydrate exploitation at the field scale. The potential gas flux generated by the kinetics of hydrate decomposition, gas flow and heat transfer was calculated, and gas production at the lab scale was mainly limited by heat transfer [23]. By considering the particle surface area during ice formation, the kinetic model has the ability to predict ice formation during gas hydrate decomposition. Some limited studies of hydrate depressurization were conducted using the kinetic model [26]. However, studies of gas hydrate decomposition kinetics during ice formation are rare.

Although significant progress has been made in the numerical simulation of natural gas hydrate decomposition characteristics, most models have overlooked the ice phase. Notably, knowledge of the effect of ice generation on some important parameters (including pressure, temperature, and permeability) remains insufficient. Additionally, the effect of ice generation on the gas production rate is unclear. The changes in these parameters, which must be considered in the process of gas hydrate exploitation, must be investigated. In this study, we