Modeling Natural Gas Productivity Recovery from a Hydrate Reservoir Well

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Abstract—The hydrocarbon deposits have stimulated worldwide efforts to understand gas production from hydrate dissociation in hydrate reservoirs well. This paper deals with the potential of gas hydrates as a source of energy which is widely available in permafrost and oceanic sediments. It discusses methods for gas production from natural gas hydrates. Authors provide a detailed methodology used to model gas productivity recovery from hydrate reservoir well. The mathematical modelling of gas dissociation from hydrate reservoir as a tool for evaluating the potential of gas hydrates for natural gas production. The simulation results show that the process of natural gas production in a hydrate reservoir is a sensitive function of reservoir temperature and hydrate zone permeability. The model couples \( n^{th} \) order decomposition kinetics with gas flow through porous media. The models provide a simple and useful tool for hydrate reservoir analysis.

Keywords—gas hydrates; natural gas production; hydrate dissociation; models; energy sources

I. INTRODUCTION

Gas hydrates are crystalline inclusion compounds in which gas molecules are held as guests in a metastable host lattice made up of water molecules. The gas hydrates are formed when gas and water mixtures are subjected to high pressure or low temperature conditions. These conditions are found in subsurface environments of deep-sea sediments and permafrost regions, where the presence of in situ hydrates has been confirmed by extensive exploration activities around the world (Goel, 2001). The high concentration of natural gas puts the energy content of hydrate-bearing formations on par with bitumen and heavy-oil reservoirs, and much higher than the energy content of other unconventional sources of gas, such as coalbed methane and tight gas (Collett, 1998). World reserves of natural gas hydrate have been estimated to be the largest fossil fuel resource among the known reserves of conventional natural gas and oil. Thus, developing methods for commercial production of natural gas from hydrates has enormous economical and strategic importance (Chuang, 2003).

Hydrate will remain a solid until formations are moved outside of the hydrate-stability region. The hydrate-stability region is a function of pressure, temperature and composition of the gas and fluid in the pore space (Williams, 2003). The hydrate dissociates when its temperature increases to above the temperature of hydrate formation at a specified pressure, or when the system pressure decrease to below the pressure of hydrate formation at a specified temperature rapture. When a well is drilled in to a hydrate reservoir, it initiates a depressurization that leads to decomposition of hydrate and release of hydrate gas.

Interest in gas hydrates started in the early part of the 19th century, mostly as a curiosity in the laboratory, when chemists made hydrates of different gases. In the 1930s, it was suggested that blockage observed in some gas-transmission pipelines was not ice, but gas hydrate. Extensive research subsequently ensued, primarily for finding ways of avoiding or delaying hydrate formation through the use of thermodynamic and kinetic inhibitors, respectively. Several recent monographs and textbooks, including that of Sloan, review these developments.

In the 1960s, another aspect was raised when gas production from naturally occurring hydrate deposits was reported in the Messoyakha field in western Siberia where an interval saturated with gas hydrate overlies the gas-saturated formation. It is believed that hydrates contributed to the long-term production of gas, when gas was simply produced from the free-gas zone. The production of the underlying free gas led to depressurization and dissociation of the upper hydrates. It is estimated that approximately 36% (5–109 m³) of the gas withdrawn from the field came from the gas hydrate. Both this field experience and recent modeling studies suggest that the production life of gas reservoirs, such as those in the Mackenzie delta of Canada that include hydrate-bearing formations at their top, can be significantly increased because of the contribution from the top hydrates (Darvish, 2004).

This work is undertaken to develop a model to predict the performance of a naturally occurring in situ hydrate reservoir.
The kinetics model is incorporated into the radical diffusivity equation using a gas mass balance in gas hydrate reservoirs, well, then, the model is solved analytically. The proposed model is used to describe the gas potential of an example reservoir and to compare gas production estimates with data from other published studies.

II. GAS HYDRATE PRODUCTION TECHNOLOGY

Even though gas hydrates are known to occur in numerous marine and Arctic settings, little is known about the technology necessary to produce gas hydrates. Most of the existing gas hydrate "resource" assessments do not address the problem of gas hydrate recoverability. From a technical point of view, all potential schemes of gas production from hydrate reservoirs need to achieve at least three objects.

- Bring the pressure and temperature conditions around hydrate particles outside the hydrate stability zone.
- Sustain the energy required for the endothermic reaction.
- Provide a means to transfer the production of decomposition to the production wells.

Of course, all these objectives must be achieved economically and safely. On this basis, several recovery processes have been suggested that can be divided broadly in three categories. Proposed methods of gas recovery from hydrates usually deal with dissociating or "melting" in-situ gas hydrates by three methods.

A. Thermal Injection

In these methods, heat is introduced into the reservoir, causing destabilization of the hydrate particles in Fig.1. (a). Klamath (1998) suggests that the introduction of thermal energy may be achieved from the surface by the injection of hot fluids, including water, brine, or steam, or may involve a down hole process, such as in-situ combustion or electric and electromagnetic heating. However, thermal methods are adversely affected by heat loss to nonproductive formations and heat left in the reservoir; the economic cost associated with such a gas-recovery technique calls for careful planning and engineering.

Initial economic evaluations (Collett, 1998) show that, for an equal volume of gas produced, thermal stimulation method is significantly more expensive than the depressurization method, while gas recovery based on inhibitor injection is probably the most expensive method. Thermal methods may, however, be preferred over the depressurization technique if the latter technique does not lead to practical rates of gas production from low heat-transfer rates.

B. Inhibitor Injection

Injecting inhibitors causes decomposition of a gas hydrate by shifting its thermodynamic-equilibrium curve in Fig.1. (b). However, their application is probably limited to small volumes because of the high cost associated with inhibitors. In the Messoyakha field, when unwanted plugging occurred, methanol and a calcium chloride solution were successfully injected for remediation to reopen flow paths in the vicinity of the wellbore.

Most of these production techniques are conceptual and have not been tested on a large scale. With the exception of the reported history of the Messoyakha field, reservoir tests for the production of gas from hydrates are in their infancy. One method of understanding the reservoir behavior during hydrate decomposition is the use of mathematical models validated against production-test results.

C. Depressurization

In this technique, the pressure of the fluids in contact with hydrate is lowered by produced in Fig.1. (c), pushing the hydrate out of its stability region and leading to its decomposition (Fig. 1). Because no extra heat is introduced into the reservoir, the heat of decomposition must be supplied from the surrounding formation. Many studies have indicated that this could be the rate-controlling step in the overall decomposition process. Therefore, this technique could be attractive primarily when a large surface area exists for heat transfer and decomposition. The presence of a free-gas zone beneath the hydrate may be essential to the success of the depressurization method.

The most common depressurization technique envisions drilling through the hydrate layer and completing the well in the free-gas zone. Gas production from this layer leads to pressure reduction and decomposition of the overlying hydrate. Gas production from the Messoyakha field was based primarily on this depressurization technique. Many people believe that the depressurization method is the most economical of the three methods and that the first commercial project for gas production from hydrate reservoir will use this technique. Some believe that ice formation that could accompany the depressurization process may hamper further decomposition, while others are of the opinion that ice formation is of no concern. If necessary, the production pressure can be designed to avoid ice formation in most cases. Similar to other proposed gas-hydrate production schemes, large volumes of water may be produced, especially if the underlying free phase is water, such as that seen in the Mallik field. This situation will require surface facilities for water handling and artificial lift in the wells if natural-gas flow cannot be sustained (Darvish, 2004).

Extracting natural gas from hydrate formations using any of the above techniques would have an impact on the formation itself and its surrounding area. In the case of undersea hydrate reserves, the dissociation and extraction would have to be done without contributing to the instability of the seafloor.
A discontinuity in the strength of the sediment column may already exist at the base of an undersea hydrate zone. This could be caused by gas hydrates inhibiting normal sediment consolidation and compaction in the region. Also, any free gas trapped below the hydrate zone could be overly compressed, resulting in an abrupt change in pressure at the zone boundary. Such a discontinuity represents a potentially unstable condition in the seafloor where gas hydrates are situated.

It should be noted that current assessment of proposed methods for gas hydrate production do not consider some of the more recently developed advanced oil and gas production schemes. For example, the usefulness of downhole heating methods such as in-situ combustion, electromagnetic heating, or downhole electrical heating has not been evaluated. In addition, advanced drilling techniques and complex downhole completions, including horizontal wells and multiple laterals, have not been considered in any comprehensive gas hydrate production scheme. Gas hydrate provinces with existing conventional oil and gas production may also provide us with the opportunity to test relatively more advanced gas hydrate production methods.

As previously noted, the low concentration of hydrates in most of the world’s marine gas hydrate occurrences raises a concern over the production technology required to produce gas from highly disseminated gas hydrate accumulations. In addition, the host-sediments also represent a significant technical challenge to potential gas hydrate production. In most cases, marine gas hydrates have been found in clay-rich unconsolidated sedimentary sections that exhibit little or no permeability. Most of the existing gas hydrate production models require the establishment of reliable flow paths within the formation to allow the movement of produced gas to the wellbore and injected fluids into the gas-hydrate-bearing sediments. It is unlikely, however, that most marine sediments possess the mechanical strength to allow the generation of significant flow paths. It is possible that in basins with significant input of coarse-grained classic sediments, such as the Gulf of Mexico or along the eastern margin of India, gas hydrates may be reserved at high concentrations in more conventional classic reservoirs, which is more analogous to the nature of gas hydrate occurrences in onshore permafrost environments (Collett, 1993; Dallimore et al., 1999).

III. MODELING GAS PRODUCTION FROM METHANE HYDRATE

This section provides a detailed methodology used to model gas production. A kinetics model is developed and hydrate decomposition model to describe gas production from the gas hydrate well.

Methane hydrate, which makes up most of naturally occurring hydrates, is composed of roughly six molecules of water for each molecule of methane. Therefore, natural gas production from dissociation of methane hydrate in an unbounded axis symmetric reservoir due to drilling of a depressurization well is studied. The reaction of methane with water to form hydrate is represented by

\[
(CH_4 \cdot 6H_2O)_{\text{solid}} \rightleftharpoons (CH_4)_{\text{gas}} + 6(H_2O)_{\text{liquid}}
\]

Under thermodynamically favorable conditions, the water molecules form a cage around the methane molecule and from the solid hydrates. When the pressure decrease or the temperature rises, the reaction reverses and the hydrate decompose into CH_4 and water.

Thehydrate reservoir is represented by a cylindrical geometry of the hydrate reservoir is represented as shown in Fig.2. As hydrates dissociate into gas, two regions are formed in the reservoir, one containing dissociated gas and other undissociated hydrates. These two regions are separated by an interface, located at \( r \), which moves as the hydrates dissociate, and the \( r_0 \) is the borehole radius, \( R \) is the effective radius of gas hydrate reservoir. When \( r=R \), the reservoir will no gas recovery again.

The hydrate dissociation results in gas release from the reservoir. If \( n_L \) represents the moles of gas released from the at time \( t \). Thus the molar rate of gas released from the reservoir is given by \( \frac{dn_L}{dt} \). This rate is proportional to the hydrate decomposition rate as the moles of gas produced from a hydrate reservoir depend on the amount of hydrate dissociated.

The hydrate dissociates by the destruction of hydrate lattice and the release of gas from its interstices. The lattice destruction depends on a driving force applied across it; in case of depressurization induced dissociation, this driving force is the differential pressure across the hydrate lattice. As the differential pressure is applied to the hydrate surface, the hydrate lattice near the surface breaks down first, thereby releasing gas from the surface itself. For the same differential pressure, the hydrate dissociation will be greater for a larger surface area of the hydrate lattice exposed to the driving force. Hence, the hydrate dissociation rate depends on the surface area of the dissociating hydrate and on the pressure differential across the hydrate surface. The differential pressure is the difference between the pressure at hydrate–gas phase equilibrium \( P_{eq} \) and the pressure for dissociation \( P_D \). Therefore, the molar rate of gas released from a hydrate reservoir is proportional to the hydrate surface area \( A_t \) and to the differential pressure \( (P_{eq} - P_D) \).

The equilibrium pressure \( P_{eq} \) is a function of the reservoir temperature. When the hydrates dissociates in the reservoir, the reservoir temperature near the dissociating surface will decrease. This decrease in temperature will cause a decrease in the equilibrium pressure \( P_{eq} \) and thus, a decrease in the driving force for further dissociation of the hydrates. Therefore, the gas release rate will decrease as the hydrate dissociation progresses. This temperature effect on the
dissociation rate can be approximated by describing the driving force \( (P_{eq} - P_D)^n \) as an nth order differential pressure \( (P_{eq} - P_D)^n \), where \( n \) is kinetics model order, the driving force is less \( (P_{eq} - P_D) \) for \( n \) values less than 1. With this simplification, the hydrate decomposition can be defined by an nth order driving force-induced decomposition kinetics model where the molar rate of gas released from the hydrate reservoir is given by

\[
\frac{dn}{dt} = A_n (P_{eq} - P_D)^n
\]  

(1)

The kinetics model described by Eq. (1) can be simplified by using gas mass balance and an appropriate equation of state. For a hydrate volume of hydrate saturation (20%) and reservoir thickness, the initial moles of gas trapped in the reservoir is by Eq. (1)

\[
n_0 = \pi (R^2 - r_0^2) h \phi \phi S_{hh} B_{hh} \frac{P_{sc}}{RT_{sc}}
\]  

(2)

where, \( \phi \) is porosity (30%), \( h \) is reservoir thickness, \( S_{hh} \) is hydrate saturation (20%) and \( B_{hh} \) is the gas hydrate formation factor and is defined as the ratio of a standard volume of gas trapped in a unit reservoir volume of the hydrate. The value of \( B_{hh} \) is from 160 to 181 SCM/m³, as a cubic meter of the hydrate is known to contain about from 160 to 181 SCM of methane gas.

Therefore, in the unit’s time, the gas recovery from reservoir is given by Eq. (3)

\[
n_L = \pi (r^2 - r_0^2) h \phi \phi S_{hh} B_{hh} \frac{P}{RT_s}
\]  

(3)

As the hydrates dissociate up to a distance \( R_D \), the hydrate volume remaining in the reservoir is

\[
n_H = \pi (R^2 - R_D^2) h \phi \phi S_{hh} B_{hh} \frac{P_{sc}}{RT_{sc}}
\]  

(4)

Rearranging Eq. (3), an expression for \( R_D \) is obtained as

\[
R_D = (n_0 - n_H)^{1/2} \left[ \frac{RT_{sc}}{\pi h \phi S_{hh} B_{hh} P_{sc}} \right]^{1/2}
\]  

(5)

This interface is assumed to be the surface where the hydrates dissociate, so the hydrate dissociation surface area, \( A_s \), is the surface area of the cylindrical s geometry at \( R \). Thus

\[
A_s = 2\pi R_D h \phi S_{hh}
\]  

(6)

Substituting Eq. (3) into Eq. (6), the molar rate of gas production becomes

\[
n_L = \frac{\pi h \phi S_{hh} (P_{eq} - P_D)^{2n} RT_s}{\eta B_{hh} P_s} t^2 + 2\pi h \phi S_{hh}
\]

(7)

IV. CONCLUSIONS

It is expected that before commercial gas production from hydrates becomes reality, technology advancements in geophysical and geological methods must lead to improved macroscopic characterization of hydrate reservoirs. Gas production from hydrate dissociation being a new area of research, the important of all these unknowns on the quality of predictions is not fully known because the study of the subject is far from complete, and its complexity is compounded by the case-specificity of the dissociation methods.

A new model is developed to predict the performance of an in situ gas hydrates. The model couples nth order decomposition kinetics with gas flow through porous media. The models provide a simple and useful tool for hydrate reservoir analysis without using any empirical correlation. The model shows that the hydrate decomposition is very slow with a pressure drive mechanism, and this low rate may be increased by using chemical enhancers.

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