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TITLE: **Fundamentals of Natural Gas and Species Flows from Hydrate Dissociation - Applications to Safety and Sea Floor Instability**

PI: Goodarz Ahmadi

INSTITUTION: Clarkson University
Potsdam, NY 13699-5725
Tel: (315) 268-2322
Fax: (315) 268-6438
Email: ahmadi@clarkson.edu

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Main Accomplishments

Production of natural gas from methane hydrate by a constant down-hole pressure well is studied in details. The completed report is described in this report. Progress was made in the numerical simulation of axisymmetric hydrate reservoirs using a computer simulation model.

A new computational model for dissociation of hydrate in a core is initiated. The new model uses a user defined subroutine for the FLUENT Code for the analysis.

PRODUCTION OF NATURAL GAS FROM METHANE HYDRATE BY A CONSTANT DOWN-HOLE PRESSURE WELL

ABSTRACT

Natural gas production from the dissociation of methane hydrate in a confined reservoir by a depressurizing down-hole well was studied. The case that the well pressure was kept constant was treated and two different linearization schemes in an axisymmetric configuration were used in the analysis. For different fixed well pressures and reservoir temperatures, approximate self-similar solutions were obtained. Distributions of temperature, pressure and gas velocity field across the reservoir were evaluated. The distance of the decomposition front from the well and the natural gas production rate as functions of time were also computed. Time evolutions of the resulting profiles were presented in graphical forms and their differences with the constant well output results were studied. It was shown that the gas production rate was a sensitive function of well pressure and reservoir temperature. The sensitivity of the results to the linearization scheme used was also studied.

INTRODUCTION

Natural gas hydrates are solid molecular compounds of water with natural gas that are formed under certain thermodynamic conditions. According to Makogon (1997) world reserves of natural gas trapped in the hydrate state have been estimated to be several times the known reserves of conventional natural gas. Developing methods for commercial production of natural gas from hydrates has, therefore, attracted considerable attention in the recent years.

Methods of decomposition of hydrates are based on shifting the thermodynamic equilibrium in a three-phase system (water-hydrate-gas). In this study we are concerned with the depressurization method by drilling a well into a hydrate reservoir. It is assumed that the well

pressure is fixed at sufficiently low level that it initiates a depressurization that leads to decomposition of hydrate and release of natural gas.

Extensive reviews of research on hydrate were reported by Englezos (1993), Makogon (1997) and Sloan (1998). Thermodynamic modeling of the hydrate decomposition process by depressurization has been studied by a number of authors. Makogon (1966, 1997) describe the process of hydrate decomposition with an analog of moving boundary ablation process. Neglecting the effect of release of water, a self-similar solution for the pressure distributions in hydrate reservoir was obtained. Verigin et al. (1980) considered the effect of water flow and described mass balance of water and gas at the decomposition front. In these earlier models hydrate decomposition was treated as an isothermal process and the thermal effects were ignored.

Holder et al. (1982) considered the variation of temperature during the hydrate decomposition. Their study was concerned with a depressurization process in a hydrate reservoir overlaying a free natural gas zone. The temperature distribution in the natural gas layer was evaluated assuming a conduction heat transfer process.

Burshears et al. (1986) extended the model of Holder et al. (1982) and considered the influence of water transport in the layer. In their model, however, only heat conduction was included in the energy equation. They concluded that the gas production by depressurization could be sustained with the supply of heat from the hydrate reservoir environment.

Yousif et al. (1991) treated the depressurization process in porous media (Berea sandstone) as a Kim-Bishnoi (Kim et al. 1987) dynamic isothermal process. Gas and water flows were included in this one-dimensional model. Time variations of permeability and porosity during the hydrate dissociation were also considered. Results for pressure and hydrate saturation profiles were also reported.

Makogon (1997) summarized the study of Bondarev and Cherskiy, where the effects of heat transfer in the porous media were included. The conductive-convective heat transfer, as well as the

effect of the throttling process was included in the energy equation. Makogon (1997) reported analytical expressions for temperature and pressure profiles for the linearized system of equations for both one-dimensional and cylindrical models. Tsypkin (2000) extended the model by including the effect of water movement in a one-dimensional model. Similarity solutions for temperature and pressure distributions were also obtained using a perturbation method.

Recently, Ahmadi et al, (2000, 2004) and Ji et al. (2001) reported numerical results for the one-dimensional model described by Makogon (1997) and made a series of sensitivity analysis of natural gas production to variation of reservoir parameters. Ji et al. (2003) studied natural gas production from a well using an axisymmetric hydrate reservoir model under various conditions. For a fixed well output, the field equations were linearized and self-similar solutions for temperature and pressure profiles in the reservoir were obtained. Time evolutions of pressure and temperature profiles in the reservoir, as well as the location of the front are evaluated and their variations were studied.

Thermal method for natural gas production from hydrate was also studied by a number of authors. Selim and Sloan (1989) studied the convective-conductive heat transfer in the reservoir using a one-dimensional model. Masuda et al. (1999) treated the process of hydrate dissociation as a Kim-Bishnoi (1987) kinetic process. Moridis et al. (1998) developed a hydrate dissociation module (EOSHYDR) for the TOUGH2 general-purpose reservoir simulator. The flow of gas and water were in the reservoir was studied and the heat transfer effects was included. Durgut (1996) simulated the hot-water injection into a hydrate reservoir. Kamath (1983) carried out a set of experiment of hydrate dissociation by hot-water injection. Recent studies on geological aspects of hydrates were reported in AGU (1999). Moridis (2002) reported his simulation results for hydrate dissociation using the EOSHYDR module.

This paper describes the problem of natural gas production from a depressurizing well in a hydrate reservoir. An axisymmetric model is used and the case that the well pressure is fixed, reservoir is partially saturated with hydrate, and the reservoir contains pressurized natural gas is

considered. The governing equations are linearized using two different schemes and a set of approximate self-similar solutions for variations of pressure, temperature and flow rate across the reservoir are obtained. The approach leads to a system of coupled algebraic equations for the location of the dissociation front, and the time varying equilibrium temperature and pressure at the front, which are solved by an iterative scheme. Numerical results for time evolutions of pressure and temperature profiles in the hydrate reservoir, the location of the front, natural gas production rate, as well as the dissociation pressure and temperature are presented in graphical form and discussed.

HYDRATE DECOMPOSITION MODEL

Clathrate hydrate is a metastable inclusion in which gas molecules are entrapped into hydrogen-bonded water lattices. Chemical reaction of methane with water to form hydrate is represented by

When the pressure decreases or the temperature rises, the reaction reverses and the hydrate decomposes into methane and water.

There are two basic structures of clathrate hydrate according to the arrangement of their cavities. The structure of in-situ methane hydrate is always structure I, one unit cell of which contains 6 large and 2 small cavities. Usually the ratio of moles of water to moles of methane gas in this structure is 6.

Suppose there is a large pressurized methane hydrate reservoir underground. Also the hydrate is assumed to coexist with free natural gas in a porous layer and keeps stable at an initial reservoir pressure P_e and reservoir temperature T_e . The specific initial hydrate conditions, P_e and T_e , along with the down-hole well pressure P_G , determines the hydrate dissociation pressure and temperature, P_D and T_D , which are slowly varying functions of time. When a well is drilled into the reservoir,

and the well pressure is below the hydrate dissociation pressure (i.e., $P_G < P_D < P_e$), the hydrate near the well is no longer stable and begins to dissociate into natural gas and water. The process of hydrate decomposition then expands outward with time. Here we assume a narrow dissociation front exists, and hydrate decomposition only occurs on this front. This moving front separates the volume of the reservoir into two zones with different phases. In the near-well zone only natural gas and water exist, while in the zone further away from the well only the solid hydrate and natural gas exist. Pressures and temperatures in these two zones gradually decrease, and the natural gas moves towards the well because of the pressure gradient, while the decomposition front moves in the opposite direction. Details of the kinetics of hydrate dissociation at this front are ignored.

It should be emphasized that the reservoir model used in this study involves several important assumptions (Makogon, 1997). The hydrate reservoir is assumed to be porous and contain natural gas. As the dissociation front moves outward, heat is supplied by gas convection to the front because of the endothermic nature of the hydrate dissociation process. Furthermore heat conduction is negligible compared to convection. The other assumptions are that during hydrate dissociation the front is a source of mass that releases water and methane gas, the movement of water is negligible small, and the gas permeability is constant. In the following analysis, we further assume that the temperature and pressure distributions are axisymmetric with respect to the well centerline, and the dissociation front is a cylinder with its axis at the well.

MATHEMATICAL MODEL

In this section, the mathematical formations for pressure and temperature fields are summarized. Consider a hydrate reservoir with a depressurizing well as shown in Figure 1. It is assumed that the well pressure is fixed. The axisymmetric pressure distribution in the reservoir is described using an analog of the classical Stefan's problem for melting

$$\frac{k_n}{2\Phi_n\mu} \left(\frac{\partial^2 P_n^2}{\partial r^2} + \frac{1}{r} \frac{\partial P_n^2}{\partial r} \right) = \frac{\partial P_n}{\partial t}, \quad (1)$$

where

$$\Phi_1 = (1 - \alpha) \Phi, \quad (2)$$

$$\Phi_2 = (1 - \beta) \Phi. \quad (3)$$

Here μ is viscosity of gas, k_n is gas permeability in zone 1 or 2, P_n is the pressure in zone 1 or 2, Φ is porosity, α is the water saturation, and β is the hydrate saturation. In Equation (1) and in the subsequent analysis, $n = 1$ corresponds to the region $r_0 < r < R(t)$, and $n = 2$ to the region $R(t) < r < \infty$, where $R(t)$ is the distance of dissociation front from the origin (located at the well), r_0 is the radius of well.

The relation between temperature T_D and pressure P_D on the dissociation front in terms of the phase equilibrium between natural gas and hydrate is

$$\log_{10} P_D = a (T_D - T_0) + b (T_D - T_0)^2 + c, \quad (4)$$

where T_0 is 273.15 K and a, b, c are empirical constants that depend on the hydrate composition. Values of a , b , and c are obtained using the least square error fit to the equilibrium pressure-temperature data of methane hydrate (Makogon, 1997, Ji et al. 2001). i.e.,

$$a = 0.0342 \text{ K}^{-1}, \quad b = 0.0005 \text{ K}^{-2}, \quad c = 6.4804,$$

where in Equation (4) P_D is in Pa.

Ji et al. (2001) showed that the prediction of Equation (4) is in good agreement with the data of Marshal et al. (1964). The mass balance for gas at the dissociation front, $R(t)$, as obtained by Vergin et al. (1980) is

$$\rho_1 v_1 - \rho_2 v_2 = -[\beta \varepsilon \rho_3 - (1 - \alpha) \rho_1 + (1 - \beta) \rho_2] \Phi \frac{dR}{dt}, \quad (5)$$

where ρ_1 is the density of natural gas in zone 1, ρ_2 is the density of natural gas in zone 2, and ρ_3 is the density of hydrate, ε is the mass fraction of gas in methane hydrate. Here v_1 and v_2 are the velocities

of natural gas in zone 1 and 2.

The densities of the natural gas in zone 1 and 2 at the dissociation front are the same. i.e.,

$$\rho_1(R, t) = \rho_2(R, t) = \rho_0 \frac{P_D T_0}{z P_0 T_D}, \quad (6)$$

where z is the gas compressibility, and ρ_0 is the gas density at std pressure P_0 and temperature T_0 . Substituting (6) into (5), it follows that

$$v_1(R, t) - v_2(R, t) = -[\varepsilon\beta \frac{\rho_3 P_0 T_D}{\rho_0 P_D T_0} z - (\beta - \alpha)]\Phi \frac{dR}{dt}. \quad (7)$$

The mass balance equation for water is given as:

$$\rho_w \Phi \alpha = (1 - \varepsilon)\rho_3 \Phi \beta, \quad (8)$$

where ρ_w is the density of water.

The temperature field of the gas-saturated layer is governed by the convective- conductive heat transfer equation that includes a temperature change because of throttling and adiabatic effects. i.e.,

$$\frac{a_n}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T_n}{\partial r} \right) = \frac{\partial T_n}{\partial t} - \frac{c_v k_n}{c_n \mu} \frac{\partial P_n}{\partial r} \left(\frac{\partial T_n}{\partial r} - \delta \frac{\partial P_n}{\partial r} \right) - \eta \frac{\Phi_n c_v}{c_n} \frac{\partial P_n}{\partial t}, \quad (9)$$

where a_n is the heat diffusivity, c_n is the heat capacity, c_v is the constant volume heat capacity of gas, δ is the throttling coefficient, and η is the adiabatic coefficient of the gas. Note that the Joule-Thompson throttling process is accounted for in Equation (9).

The boundary conditions for a fixed well pressure are

$$P_1(r_0, t) = P_G, \quad (10)$$

$$P_2(r, 0) = P_2(\infty, t) = P_e, \quad (11)$$

$$P_1(R(t), t) = P_2(R(t), t) = P_D(T_D), \quad (12)$$

$$T_2(r, 0) = T_2(\infty, t) = T_e, \quad (13)$$

$$T_1(R(t), t) = T_2(R(t), t) = T_D(t). \quad (14)$$

Note that for a constant well pressure, the equilibrium conditions at the front are slowly varying

functions of time.

LINEARIZATION AND SELF-SIMILAR SOLUTIONS

To be able to find closed form solutions, Equation (1) must be linearized. In the earlier works (Makogon, 1997; Ahmadi et al., 2000; Ji et al., 2001) for a Cartesian coordinate, the reservoir and well pressures were used to, respectively, linearize the pressure equation in the hydrate and gas zones. Ji et al (2003) used the reservoir and the dissociation pressure to linearize the corresponding pressure equations for an axisymmetric geometry for their constant production rate analysis. Here for the case of fixed downhole pressure well case, two linearization methods are used in order to assess the sensitivity of the results to the choice of scheme.

LINEARIZATION METHOD I

In the first approach, the dissociation pressure, P_D , is used for linearization in the gas zone and the reservoir pressure, P_e , is used for linearization in the hydrate zone. i.e.,

$$\frac{\partial P_1^2}{\partial t} \approx 2P_D \frac{\partial P_1}{\partial t} \quad \frac{\partial P_2^2}{\partial t} \approx 2P_e \frac{\partial P_2}{\partial t} . \quad (15)$$

While P_D is a slowly varying function of time, it is assumed that $\frac{\partial P_D}{\partial t}$ is negligibly small.

Equation (1) may then be linearized as

$$\frac{\partial P_n^2}{\partial r^2} + \frac{1}{r} \frac{\partial P_n^2}{\partial r} = \frac{1}{\chi_n} \frac{\partial P_n^2}{\partial t} , \quad (16)$$

where

$$\chi_1 = \frac{k_1 P_D}{\Phi(1-\alpha)\mu} \quad \chi_2 = \frac{k_2 P_e}{\Phi(1-\beta)\mu} . \quad (17)$$

Approximate self-similar solutions of Equation (16) with boundary conditions (10)-(14) are given as

$$P_1^2 = P_G^2 + (P_D^2 - P_G^2) \frac{E_i(-\lambda_1^2) - E_i(-\alpha_0^2)}{E_i(-\alpha_1^2) - E_i(-\alpha_0^2)}, \quad (18)$$

$$P_2^2 = P_e^2 - (P_e^2 - P_D^2) \frac{E_i(-\lambda_2^2)}{E_i(-\alpha_2^2)}, \quad (19)$$

where

$$\lambda_n = \frac{r}{2\sqrt{\chi_n t}}, \quad \alpha_n = \sqrt{\frac{\gamma}{4\chi_n}}, \quad \alpha_0(t) = \frac{r_0}{2\sqrt{\chi_1 t}}, \quad (20)$$

$$E_i(-\xi) = -\int_{\xi}^{\infty} \frac{e^{-u}}{u} du, \quad (21)$$

$$R(t) = \sqrt{\gamma t}. \quad (22)$$

Here, γ is a slowly varying function of time (nearly constant) and r_0 is the radius of the well. It should be emphasized that the solutions given by Equations (18) and (19) are only approximately self-similar due to the time dependence of $\alpha_0(t)$ that also leads to γ , P_D and T_D to depend on time.

Under the condition that the hydrate reservoir contains free methane gas, neglecting the conductive heat transfer in the porous medium, which is several orders of magnitude smaller than the convection heat transfer, Equation (9) becomes

$$\frac{\partial T_n}{\partial t} - \frac{c_v k_n}{c_n \mu} \frac{\partial P_n}{\partial r} \left(\frac{\partial T_n}{\partial r} - \delta \frac{\partial P_n}{\partial r} \right) - \eta \frac{\Phi_n c_v}{c_n} \frac{\partial P_n}{\partial t} = 0. \quad (23)$$

Approximate self-similar solutions to the Equation (23) satisfying the boundary conditions (10)-(14) are given as,

$$T_1 = T_D + A_1 \delta \left[E_i(-\lambda_1^2) - E_i(-\alpha_1^2) + \left(\frac{\eta}{\delta} B_1 - 1 \right) (\Psi_1(\lambda_1^2) - \Psi_1(\alpha_1^2)) \right], \quad (24)$$

$$T_2 = T_e + A_2 \delta \left[E_i(-\lambda_2^2) - \left(\frac{\eta}{\delta} B_2 - 1 \right) \Psi_2(\lambda_2^2) \right], \quad (25)$$

where

$$\Psi_1(\xi) = \int_0^\xi \frac{e^{-\eta}}{\eta + C_1 e^{-\eta}} d\eta, \quad \Psi_2(\xi) = \int_\xi^\infty \frac{e^{-\eta}}{\eta + C_2 e^{-\eta}} d\eta, \quad (26)$$

$$A_1 = \frac{1}{2} \frac{1}{E_i(-\alpha_1^2) - E_i(-\alpha_0^2)} \frac{P_D^2 - P_G^2}{P_D}, \quad A_2 = -\frac{1}{2 E_i(-\alpha_2^2)} \frac{P_e^2 - P_D^2}{P_e}, \quad (27)$$

$$B_1 = \frac{\Phi_1 c_v}{c_1}, \quad B_2 = \frac{\Phi_2 c_v}{c_2}, \quad (28)$$

$$C_1 = \frac{1}{2} \frac{P_D^2 - P_G^2}{P_D} \frac{c_v}{c_1} \frac{1}{E_i(-\alpha_1^2) - E_i(-\alpha_0^2)} \frac{k_1}{\mu \chi_1}, \quad C_2 = -\frac{P_e^2 - P_D^2}{P_e} \frac{c_v}{c_2} \frac{1}{2 E_i(-\alpha_2^2)} \frac{k_2}{\mu \chi_2}. \quad (29)$$

Note that A_1 and C_1 are also slowly varying functions of time.

LINEARIZATION METHOD II

In the second linearization approach, the constant well pressure is used for linearizing Equation (1) in the gas zone. i.e.,

$$\frac{\partial P_1^2}{\partial t} \approx 2 P_G \frac{\partial P_1}{\partial t}, \quad \frac{\partial P_2^2}{\partial t} \approx 2 P_e \frac{\partial P_2}{\partial t}. \quad (30)$$

In this case, Equations (16) and (23) and their approximate self-similar solutions given by Equations (18), (19), (24) and (25) remain the same. However, the expression for parameters χ_1 , A_1 , and C_1 are now given as

$$\chi_1 = \frac{k_1 P_G}{\Phi(1 - \alpha)\mu}, \quad (31)$$

$$A_1 = \frac{1}{2} \frac{1}{E_i(-\alpha_1^2) - E_i(-\alpha_0^2)} \frac{P_D^2 - P_G^2}{P_G}, \quad (32)$$

$$C_1 = \frac{1}{2} \frac{P_D^2 - P_G^2}{P_G} \frac{c_v}{c_i} \frac{1}{E_i(-\alpha_1^2) - E_i(-\alpha_0^2)} \frac{k_1}{\mu \chi_1}. \quad (33)$$

As noted before, A_1 and C_1 are slowly varying functions of time and the values of other parameters remain the same.

It should be emphasized that the values of pressure P_D and temperature T_D at the dissociation front, and parameter γ (which determines the motion of the decomposition front) are still unknown. Evaluating Equation (25) at the dissociation front, (i.e., $\lambda_2 = \alpha_2$), it followed that

$$T_D = T_e + A_2 \delta [E_i(-\alpha_2^2) - (\frac{\eta}{\delta} B_2 - 1) \Psi_2(\alpha_2^2)]. \quad (34)$$

The equilibrium pressure P_D and the equilibrium temperature T_D are related through Equation (4). Substituting Equations (18) and (19) into Equation (7), we obtain the equation for determining

the parameter, γ . i.e.,

$$k_1 (P_D^2 - P_G^2) \frac{e^{-\alpha_1^2}}{E_i(-\alpha_1^2) - E_i(-\alpha_0^2)} + k_2 (P_e^2 - P_D^2) \frac{e^{-\alpha_2^2}}{E_i(-\alpha_2^2)} = A \sqrt{\gamma}, \quad (35)$$

where

$$A = [\varepsilon \beta \frac{\rho_3 P_0 T_D}{\rho_0 T_0} z - (\beta - \alpha) P_D] \Phi \mu. \quad (36)$$

Equations (4), (34) and (35) are three nonlinear coupled equations for determining γ , T_D and P_D . An iterative scheme is used for evaluating the numerical values of these parameters. In this model the resulting dissociation pressure and temperature depend on well pressure, reservoir pressure and reservoir temperature, but also evolve gradually with time due to the time dependence of $\alpha_0(t)$ and $E_i(-\alpha_0^2)$. Thus, coupled Equations (4), (34) and (35) are solved for every time after initiation of the depressurization, and dissociation temperature and pressure are updated at every time step. The approximate solution is expected to be reasonable as long as the dissociation pressure

and temperature and parameter γ are slowly varying functions of time.

The production rate of methane gas per unit length of the well is then given as

$$Q = \frac{\pi k_1}{\mu} \frac{\rho_0}{P_0} \left[r \frac{\partial P_1^2}{\partial r} \right]_{r=r_0} = 2\pi \frac{k_1}{\mu} \frac{\rho_0}{P_0} \frac{(P_D^2 - P_G^2) e^{-\alpha_0^2(t)}}{E_i(-\alpha_1^2) - E_i(-\alpha_0^2)}. \quad (37)$$

Equation (37) shows that the well production rate varies with time (will be shown to decrease with time). While P_D varies slightly with time, the exponential dependence on $\alpha_0(t)$ is the main reason for the time variation of Q .

RESULTS

This section presents numerical results for the time evolution of pressure and temperature profiles in a hydrate reservoir under various conditions. In addition, time variations of gas production, location of the dissociation front, and the dissociation pressure and temperature are also evaluated. The conditions listed in Appendix A and an initial reservoir pressure of 15MPa are used in these simulations.

As noted before, two linearization techniques were used in the analysis. The one that used the dissociation pressure, P_D , for the linearizing Equation (1) in gas zone is referred to as "Linearization Method I." "Linearization Method II" is when the well pressure, P_G , is used for linearization. In Table 1, values of the dissociation temperature and pressure at the dissociation front and parameter γ for different well pressures and initial temperatures are listed. Since these vary slightly with time, in Table 1 the values of P_D , T_D and γ at 120 days after production are listed for comparison. Here the permeability in gas zone is 5.2 md and the hydrate zone permeability is 0.4 md. For the range of parameter studied, the differences in P_D , T_D and γ for the Linearization Methods I and II are negligibly small, and the values listed in Table I are for both linearization methods. As noted before, coupled Equations (4), (34) and (35) are solved for evaluating the values of dissociation pressure and temperature and parameter γ . Among these, only the values of $\alpha_0(t)$ and $\alpha_1(t)$ in the

first term of Equation (35) are affected through parameter i_1 with the choice of linearization methods. However, magnitude of the first term in Equation (35) is comparatively small. Thus, the values of dissociation temperature, pressure and parameter γ remain the same within the accuracy of the computation.

Table 1 shows that the dissociation pressure and temperature vary with the variations of well pressure. As the well pressure increases, the dissociation pressure and temperature increase slightly. However, P_D and T_D are sensitive functions of reservoir temperature. A decrease of 2 K in the reservoir temperature drops the dissociation pressure by about 1.9 MPa, and reduces parameter γ by about 200%. An additional 2 K drop in the reservoir temperature leads to a reduction of dissociation pressure by about 1.8 MPa and reduces γ by a factor of 8.

For Linearization Methods I and II, Table 2 shows the values of dissociation temperature and pressure at the front at different times. It is seen that the dissociation pressure and temperature increase slightly with time, while the parameter γ decreases. This means that when the well pressure is fixed, the dissociation front movement slows down as time increases. Additional details of the time variation of dissociation temperature and pressure, and parameter γ are provided in the subsequent sections.

For a well pressure of 2 MPa and reservoir pressure of 15 MPa, Figure 2 shows variations of pressure and temperature profiles at different times. Here the results are based on Linearization Method I. The hydrate reservoir is divided into two zones by the dissociation front, and the temperature variations in the two zones are quite different. Figure 2a shows that the temperature decreases gradually from the undisturbed reservoir value far from the front to the dissociation temperature at the front. The temperature gradient in the hydrate zone is largest near the front. In the gas zone, the temperature also decrease from the dissociation front to the well and drops sharply to its minimum value at radius of the well. The near well temperature variations are more clearly seen from Figure 2b. The temperature profiles in the hydrate and the gas zones are approximate self-similar, since the dissociation temperature varies slightly with time.

The corresponding pressure profiles for different times are presented in Figure 2c. The pressure decreases gradually from the reservoir pressure to the dissociation pressure at the front, and then decreases toward the well to its minimum value at radius of the well. For the zone permeabilities of $k_1 = 5.2$ md and $k_2 = 0.4$ md, the change of slope of the pressure profile at the front is significant. Figure 2d shows details of variation of the pressure profiles in gas zone. The pressure decreases gradually from the dissociation front and drops sharply near the well. Figures 2b and 2d show that the pressure profiles for different times are also approximately self-similar, and expand outward as the dissociation front moves away from the well.

For a fixed well pressure of 2 MPa, Figure 3 shows time evolution of mass flow and mass flux profiles in the reservoir for Linearization Method I. Figure 3a shows that the mass flux has its expected decreasing trend with the distance from the well, but it also decreases slightly with time. The expected jump at the dissociation front due to the dissociation of hydrate is also clearly noticed from this figure. The jump moves outward and its magnitude becomes smaller with time as the dissociation front penetrates deeper into the hydrate reservoir.

Figure 3b presents the variation of total mass flow per unit height of the well. (The total mass flow is the product of the mass flux and the surface area of the cylinder of radius r .) For a fixed time, the total mass flow is roughly constant in the gas and the hydrate zones, with a jump at the dissociation front. For a fixed well pressure, however, total mass flow decreases with time. Figure 3b also clearly shows the amount of natural gas generated by hydrate dissociation at the front and its variation with time. A careful examination of this figure shows that the amount of natural gas generated by hydrate dissociation at the front decreases slightly with time.

For the same reservoir conditions, Figure 4 compares the temperature, pressure, mass flux and total mass flow profiles as evaluated by different linearization methods. Here the reservoir temperature and pressure are, respectively, 287 K and 15 MPa, and well pressure is 2 MPa. In this figure, solid and dashed lines correspond, respectively, to Methods I and II. Figure 4 shows that the

pressure, mass flux and total mass flow are nearly identical for both linearization methods. The only exception is the temperature profile in the gas zone, for which Method I leads to higher temperatures when compared to Method II. It may then be concluded that the pressure and mass flux profiles are not sensitive to linearization method used.

Figure 5 shows the pressure and temperature profiles for a well pressure of 3 MPa. Here Linearization Method I is used and the reservoir pressure and temperature are kept constant at 15 MPa and 287 K. Except for somewhat slower movement of the front, variations of pressure and temperature profiles in these figures are quite similar to those shown in Figure 2. In the hydrate zone, the pressure and temperature decrease from their reservoir values at large distances to the dissociation values at the front. Comparatively, large gradients occur near the front on the hydrate side. The pressure and temperature in the gas region then decrease rather sharply toward their minimum values at the well wall.

Time evolutions of mass flux and total mass flow profiles in the reservoir for the same conditions as of Figure 5 are shown in Figure 6. Except for the lower magnitudes, the mass flux and the total mass flow profiles are quite similar to those shown in Figure 3. The movement of the dissociation front can also be clearly seen from this figure.

Under the same reservoir conditions, when the well pressure is 4 MPa, the temperature and pressure profile in the reservoir are shown in Figure 7 and the corresponding mass flux and mass flow rate are plotted in Figure 8. These figures show that the dissociation front moves at much slower rate when the well pressure increases. The temperature also becomes somewhat higher and the well temperature becomes noticeably larger in comparison with the case that the well pressure was kept as 2 MPa. Other features of pressure and temperature profiles in the hydrate zone are quite similar to those for lower well pressures. The general features of mass flux and mass flow profiles are also quite similar to those for lower well pressures.

For the case that the well pressure is 2 MPa, but the reservoir temperature is 285 K (2 K lower than the case shown in Figure 2), the pressure and temperature profiles are presented in Figure 9. While these profiles are quite similar to those shown in Figure 2, the dissociation pressure and temperature are smaller. The movement of the front also slows down for this lower-temperature reservoir. This observation further shows the importance of heat transfer in hydrate dissociation and production processes. In this cylindrical model, the heat required for hydrate dissociation must be supplied by the hydrate reservoir. Therefore, the reservoir temperature becomes an important controlling parameter. (It should be emphasized that, for natural hydrate reservoirs, heat could also be transferred from the sides, which would significantly affect the natural gas production process.)

Figure 10 shows the temperature and pressure profiles when the reservoir temperature is 283 K, the other reservoir conditions are kept fixed, and Linearization Method I is used. Comparison of Figure 10 with Figures 2 and 9 shows that the temperature and the pressure profiles are quite similar, while the movement of the dissociation front is noticeably slowed down.

Mass flux and mass flow profiles for reservoir temperature of 283 K and 285 K are compared in Figure 11. It is seen that the general features of the mass flux and mass flow rate for different reservoir temperatures are similar, the dissociation front moves faster as when the reservoir temperature is higher.

Figure 12 compares the predicted temperature, pressure mass flow and mass flux profiles with different linearization method. Here the reservoir temperature is 283 K, reservoir pressure is 15 MPa and well pressure is 2 MPa. This figure shows that the pressure, mass flux and mass flow profiles are roughly identical for the two linearization methods. That is, the pressure and mass flow are insensitive to the linearization method used. The main difference is seen for the temperature profiles in gas zone that appears to be quite sensitive to the linearization method used. It is seen that linearization Method I leads to higher temperatures in the gas zone when compared to Method II.

As note before, when the well pressure is kept fixed, the dissociation temperature and pressure and parameter γ vary slowly with time. Figure 13 shows time variation of dissociation temperature and pressure, and parameter γ for different well pressures as computed with different linearization methods. Figure 13a,b show that the dissociation temperature and pressure increase slightly with time slightly. The dissociation temperature increases by about 0.2 K and dissociation pressure by about 0.1 MPa before approaching their asymptotic roughly stationary values. These observation justifies the assumptions made in the derivation of the approximate linearized governing equations. Figure 13c indicates that parameter γ decreases gradually with time and the amplitude of the time variation increases as reservoir pressure decreases. Figure 13 also shows the solid line and the dashed line for two linearization methods used cannot be distinguished. That is the two linearization methods lead to almost identical dissociation temperature and pressure, and parameter γ .

Time variations of dissociation temperature and pressure, and parameter γ for different reservoir temperatures are shown in Figure 14. Similarly to Figure 13, for a fixed reservoir temperature, the dissociation temperature and pressure increase very slightly with time and parameter γ decreases slightly. All quantities approach their asymptotic values and the slowing varying assumption appears to be reasonable.

For fixed reservoir and well pressures, time evolutions of dissociation front and the well production rate for different reservoir temperatures as predicted by both linearization methods are shown in Figure 15. It is observed that the reservoir temperature significantly affects the motion of the front and the well output. When the reservoir temperature increases by about 2 to 4 K, the distance of the dissociation front from the well decreases by about 100 to 500 percent, and the well output increases by about 25 to 50 percent. Figure 15 also shows both linearization methods lead to roughly identical time evaluation of the dissociation front movement and gas production rate. That is the estimated production rate is insensitive to the linearization method used.

Figure 16 shows the movement of the dissociation front and the natural gas production for different well pressures as predicted by both linearization methods. Here the reservoir conditions are kept fixed at 15 MPa and 287 K. Figure 16a shows the distance of the front from the well increases roughly proportional to the square root of time. As the well pressure increases, the motion of the front also increases. Figure 16b shows time variations of natural gas output per unit height of the well for different well pressures. It is seen that the output rate decreases gradually with time. For fixed reservoir conditions, the well output is also a sensitive function of well pressure, and the production rate decreases as the well pressure increases. Similarly to Figure 15, the two linearization methods lead to roughly identical dissociation front movement and natural gas output.

In an earlier work, Ji, et al. (2003) reported their simulation results for the case that the natural gas output was fixed. In that case, the well pressure decreases with time. Figure 17 compares the present model predictions for the reservoir temperature and pressure profiles for a fixed well pressure with the corresponding profiles evaluated earlier for a constant output rate. Figures 17a and 17c the profiles after 42 days of operation are shown for the case that the well pressure is fixed as 2 MPa. Here linearization Method I is used, and the natural gas output is 0.04 kg/s. In Figures 17b and 17d, show the profiles as predicted by the earlier work of Ji et al. (2003) for a constant natural gas output rate of 0.04 kg/s, Figure 17 shows that the predicted temperature and pressure profiles and the corresponding dissociation temperature and pressure are roughly the same. That is the present model predictions are in agreement with the earlier ones.

Similarly, the present model predictions for the mass flux and mass flow rate profiles for a fixed well pressure are compared with those evaluated for a constant output rate in Figure 18. The conditions are identical to those described for Figures 17. That is after 42 days of operation the well pressure is 2 MPa and the natural gas output is 0.04 kg/s. It is seen that the predicted mass flux and mass flow rate profiles are roughly the same, and the present model predictions are in good agreement with this predicted for a constant output well.

CONCLUSIONS

Natural gas production from dissociation of methane hydrate in confined, pressurized reservoirs is studied. An axisymmetric model is used and the time evolutions of pressure and temperature profiles, as well as the well out put for fixed down hole pressure are evaluated. The sensitivity to variation of well pressure and reservoir temperature are also studied. On the basis of the presented results, the following conclusions are drawn:

- i. Under favorable conditions natural gas can be produced from hydrate reservoirs by a depressurization well.
- ii. The natural gas production rate is controlled by the reservoir pressure and temperature conditions and the well pressure.
- iii. For an infinite homogenous hydrate reservoir containing natural gas and operating under a fixed well pressure, the dissociation pressure and temperature are slowly varying functions of time, and mainly depend on the reservoir conditions and the well pressure.
- iv. For a fixed reservoir pressure and temperature, the well output increases and the speed and the dissociation front moves faster as the well pressure decreases.
- v. For fixed reservoir and well pressures, the gas production rate increases significantly as the reservoir temperature increases.
- vi. For a fixed down hole pressure, the present model predicts that the distance of the dissociation front from the well increases roughly proportional to the square root of time, and the production rate decreases with time..
- vii. The two linearization methods used in the analysis lead to roughly similar results for pressure profiles and the time evolution of well output and the movement of dissociation front. The

temperature profiles in the gas zone show some differences depending on the linearization scheme used.

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Appendix A: Nomenclature and Values of Parameters

a,b,c	empirical constants in Equation (8)
a	0.0342 K^{-1}
b	0.0005 K^{-2}
c	6.4804
a_n	thermal diffusivity of zones (m^2/s)
c_v	volume heat capacity of gas ($3000 \text{ J/K}\cdot\text{Kg}$)
c_1	heat capacity of zone 1 ($2400.2 \text{ J/K}\cdot\text{Kg}$)
c_2	heat capacity of zone 2 ($1030.2 \text{ J/K}\cdot\text{Kg}$)
k_1	phase permeability of gas in zone 1 (12md)
k_2	phase permeability of gas in zone 2 (10md)
r_0	the radius of the well
t	time
v_1	velocity of natural gas in zone 1
v_2	velocity of natural gas in zone 2
x	distance
z	compressibility of gas (0.88)
P_0	atmospheric pressure ($1.01 \times 10^5 \text{ Pa}$)
P_D	hydrate decomposition pressure
P_e	reservoir pressure at initial time (15MPa)
P_G	pressure at the well (MPa)
P_n	pressure in zone 1 or 2
Q	the production rate of methane gas per unit length of well
R	the radius of the decomposition front
T_D	hydrate decomposition temperature (K)
T_e	reservoir temperature at initial time (K)
T_n	temperature in zone 1 or 2
T_0	273.15K
α	water content of pores (0.15)
β	hydrate saturation of a layer (0.19)
γ	the constant which determines the movement velocity of decomposition front

δ	throttling coefficient of gas (8×10^{-7} K/Pa)
ε	mass fraction of gas in methane hydrate (0.129)
η	adiabatic coefficient of gas (3.2×10^{-6} K/Pa)
ρ_0	density of methane gas at atmospheric pressure P_0 and temperature T_0 . (0.706 kg/m^3)
ρ_3	density of hydrate ($0.91 \times 10^3 \text{ kg/m}^3$)
ρ_w	density of water ($1.0 \times 10^3 \text{ kg/m}^3$)
μ	viscosity of gas (methane) (1.5×10^{-5} Pa·S)
Φ	porosity (0.2)
Φ_1	$(1-\alpha)\Phi$, content of free gas at zone 1
Φ_2	$(1-\beta)\Phi$, content of free gas at zone 2

Table 1. Values of dissociation temperature and pressure and parameter γ (at 120 days) for given reservoir and well conditions for a reservoir with $k_1 = 5.2$ md and $k_2 = 0.4$ md

P_e (MPa)	T_e (K)	P_G (MPa)	T_D (K)	P_D (MPa)	γ (m ² /sec)
15	283	2	275.64	3.72	3.43×10^{-7}
15	285	2	277.56	4.39	2.03×10^{-6}
15	287	2	279.47	5.23	1.19×10^{-5}
15	287	3	279.65	5.32	6.25×10^{-6}
15	287	4	279.94	5.47	1.71×10^{-6}

Table 2. Time evolutions of dissociation temperature and pressure and parameter γ for Linearization Method I for a reservoir with $k_1 = 5.2$ md and $k_2 = 0.4$ md, $P_e = 15$ MPa, $T_e = 287$ K and well pressure $P_G = 2$ MPa

Time (days)	T_D (K)	P_D (Mpa)	γ (m ² /sec)
30	279.34	5.17	1.84×10^{-5}
60	279.41	5.2	1.47×10^{-5}
90	279.44	5.22	1.3×10^{-5}
120	279.47	5.23	1.19×10^{-5}

Figure 1. Schematic of an axisymmetric hydrate reservoir.

Figure 2. Time variations of pressure and temperature profiles for a well pressure of 2MPa and a reservoir temperature of 287K. (Linearization method I.) (a),(c) Far field. (b),(d) Near field.

Figure 3. Mass flux and mass flow profiles for a reservoir temperature of 287K and a well pressure of 2MPa. (Linearization Method I.)

Figure 4. Comparison of pressure, temperature, mass flux and mass flow profiles for a well pressure of 2MPa and a reservoir temperature of 287K for different linearization methods.
(_____ Method I, - - - - Method II.)

Figure 5. Time Variations of pressure and temperature in the reservoir for a well pressure of 3MPa and a reservoir temperature of 287K.
(Linearization method I.)

Figure 6. Mass flux and mass flow profiles for a reservoir temperature of 287K and a well pressure of 3MPa. (Linearization method I.)

Figure 7. Time variations of temperature and pressure in the reservoir for a well pressure of 4MPa and a reservoir temperature of 287K. (Linearization method I.)

Figure 8. Mass flux and mass flow profiles for a reservoir temperature of 287K and a well pressure of 4MPa. (Linearization method I.)

Figure 9. Time variations of temperature and pressure in the reservoir for a well pressure of 2MPa and a reservoir temperature of 285K. (Linearization method I.)

Figure 10. Time variations of temperature and pressure in the reservoir for a well pressure of 2MPa and a reservoir temperature of 283K. (Linearization method I.)

Figure 11. Mass flux and mass flow profiles for a well pressure of 2MPa with different reservoir temperatures. (Linearization method I.)

Figure 12. Comparison of pressure and temperature profiles, mass flux and mass flow for a well pressure of 2MPa and a reservoir temperature of 283K for two linearization methods. (Solid line: method I. Dashed line: method II.)

Figure 13. Comparison of time variations of decomposition temperature, pressure and parameter γ for different well pressures for two linearization methods. (Solid line: method I. Dashed line: method II.)

Figure 14. Comparison of time variations of dissociation temperature and pressure and parameter γ for different reservoir temperatures for two linearization methods. (Solid line: method I. Dashed line: method II).

Figure 15. Comparison of time variations of distance of dissociation front and natural gas output for different reservoir temperatures for two linearization methods. (Solid line: method I. Dashed line: method II).

Figure 16. Comparison of time variations of distance of dissociation front and natural gas output for different well pressures for two linearization methods. (Solid line: method I. Dashed line: method II).

Figure 17. Comparison of time variations of pressure and temperature profiles for a well output of 0.04kg/s and a reservoir temperature of 287K for different operation conditions. ((a),(c) Fixed well pressure. (b),(d) Fixed output).

Figure 18. Comparison of mass flux and mass flow profiles for a reservoir pressure of 15MPa a well natural gas output of 0.04kg/s for different operation conditions. ((a),(c) fixed well pressure. (b),(d) Fixed gas output).

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