

NATURAL GAS PRODUCTION FROM HYDRATE DISSOCIATION: A COMPARISON OF AXISYMMETRIC MODELS

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This paper describes an axisymmetric model for natural gas production from the dissociation of methane hydrate in a confined reservoir by a depressurizing well. During the hydrate dissociation, heat and mass transfer in the reservoir are analyzed. The system of governing equations is solved by a finite difference scheme. For different well pressures and reservoir temperatures, distributions of temperature and pressure in the reservoir, as well as the natural gas production from the well are evaluated. The numerical results are compared with those obtained by the linearization method. It is shown that the gas production rate is a sensitive function of well pressure.

1 INTRODUCTION

Natural gas hydrates are solid molecular compounds of water with natural gas that are formed under certain thermodynamically favorable conditions. According to Makogon (1997), there are tremendous reservations of natural gas trapped in hydrates in the permafrost, the continental shell and in the ocean around the globe. Thus, developing methods for commercial production of natural gas from hydrates have attracted considerable attention in the recent years.

Extensive reviews of properties of hydrates were provided by Sloan (1998), Makogon (1974,1997) and Englezos (1993). Hydrate dissociates when its phase equilibrium breaks down due to increase in temperature or reduction in pressure. In this paper the potential for natural gas production from hydrate reservoir by depressurization is studied. When a well is drilled into a hydrate reservoir, the reservoir pressure decreases to below the pressure of hydrate formation at a specified temperature, and that leads to the dissociation of hydrate and release of natural gas. It is assumed that the reservoir is partially saturated with hydrate and contains pressurized natural gas. It is also assumed that the well is kept at a constant pressure. The presented axisymmetric model, includes the energy and mass balance at the dissociation front and accounts for heat conduction in the hydrate zone of the reservoir. The resulting system of coupled governing equations is solved using a finite-difference numerical scheme in conjunction with an iterative procedure. Numerical solutions for time evolutions of pressure and temperature profiles in the hydrate reservoir, as well as the location of dissociation front are obtained for several well pressures and reservoir temperatures. The simulation results are compared with those obtained earlier by a linearization approach and discussed. It is shown that the natural gas production rate

is a sensitive function of well pressure and reservoir temperature.

2 HYDRATE DISSOCIATION MODEL

Consider an unbounded methane hydrate reservoir underground that is partially saturated with solid hydrate and also contains pressurized natural gas at the reservoir pressure P_e and reservoir temperature T_e . At this reservoir pressure, the hydrate must be stable, with $P_e > P_D$, where P_D is the hydrate dissociation pressure at dissociation temperature T_D . When a well is drilled into the reservoir, the pressure in the well drops to a certain value less than $P_D < P_e$. The hydrate near the well becomes unstable and dissociates into natural gas and water. The process of hydrate dissociation then expands radially outward from the well with time. It is assumed that the hydrate dissociation occurs in a narrow region, which can be treated as the dissociation front. This moving cylindrical front separates the volume of the reservoir into two zones with different phases. The near-well gas-zone contains natural gas and liquid water, while the hydrate-zone beyond the dissociation front contains the solid hydrate and natural gas. Pressures and temperatures in these two zones gradually decrease, as the natural gas flows towards the well, while the dissociation front moves away from the well.

Here it is assumed that the temperature and pressure distributions are axisymmetric with respect to the well centerline. The dissociation front is also a cylinder with its axis at the well. The pressure and temperature at the dissociation front are the equilibrium pressure, P_D , and temperature, T_D , both of which are functions of time.

3 MATHEMATICAL MODEL

Figure 1 shows the axisymmetric model used in the computation. In this figure, the well radius is r_0 . A cylindrical part of the reservoir with a radius of $L = 100$ m is analyzed in the present study. The computation domain ranges from $r=r_0$, where the well pressure is fixed at P_G . At $r = L$, it is assumed that the reservoir pressure and temperature are, respectively, fixed at P_e and T_e . In this figure the dissociation front, which is located at $R(t)$, separates the reservoir into two zones. The region $r_0 < r < R(t)$ is referred to as the gas zone, and the area $R(t) < r < L$ is the hydrate zone. The dissociation front $R(t)$ moves outward as the gas production from the well continues.

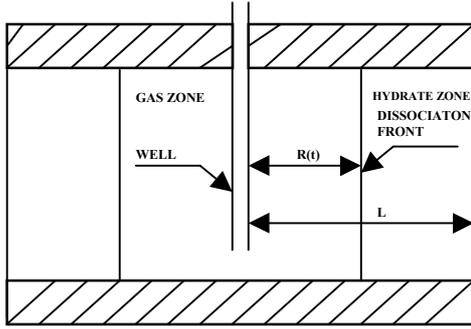


Figure 1. Schematics of the hydrate reservoir for the axisymmetric model.

In the subsequent analysis, subscript n identifies the regions, with $n=1$ or 2 corresponding to the gas zone or the hydrate zone respectively. Pressure distribution in the reservoir is governed by:

$$\frac{\partial P_n}{\partial t} = a_n \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial P_n^2}{\partial r} \right) \quad (1)$$

where

$$a_n = \frac{k_n}{\Phi_n \mu} \quad (2)$$

and

$$\Phi_1 = (1 - \alpha) \Phi \quad (3)$$

$$\Phi_2 = (1 - \beta) \Phi \quad (4)$$

Here P_n and k_n are the pressure and the gas permeability, respectively, μ is the gas viscosity, α is the water saturation, β is the hydrate saturation, Φ is the porosity,

Φ_1 is the content of free gas in the gas zone, and Φ_2 is the content of free gas in the hydrate zone.

The velocity of natural gas v_n in the gas and the hydrate zones is given by Darcy's law. i.e.,

$$v_n = -\frac{k_n}{\mu} \frac{\partial P_n}{\partial r} \quad (5)$$

Assuming that the time variation of gas density is small, the heat transfer equation in the gas zone is given as

$$\frac{\partial T_1}{\partial t} + v_1 \frac{\partial T_1}{\partial r} = 0 \quad (6)$$

where T_1 is the temperature, and v_1 is the velocity of natural gas in the gas zone. Here heat conduction in the gas zone, which is much smaller than the heat convection, is neglected.

The heat transfer equation in the hydrate zone is given as

$$\frac{\partial T_2}{\partial t} + v_2 \frac{\partial T_2}{\partial r} = \alpha_2 \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T_2}{\partial r} \right) \quad (7)$$

where α_2 is heat diffusivity in the hydrate zone.

In general, the equilibrium temperature and pressure at the dissociation front are functions of time. The phase equilibrium relation between temperature T_D and pressure P_D at the dissociation front is given as (Makogon, 1997)

$$\log_{10} P_D = A_b (T_D - T_0) + B_b (T_D - T_0)^2 + C_b \quad (8)$$

where T_0 is 273.15K and a, b, c are empirical constants that depend on the hydrate composition. Values of a , b , and c are obtained from the equilibrium pressure-temperature data of methane hydrate. Using the least square fit method, it follows that (Ji et al. 2001)

$$A_b = 0.0342 \text{ K}^{-1}, \quad B_b = 0.0005 \text{ K}^{-2}, \quad C_b = 6.4804$$

where in Equation (8) P_D is in Pa.

The process of hydrate dissociation at the dissociation front is an endothermic phase-change process. The dissociation heat per kilogram of hydrate in J/kg is given as (Kamath, 1983)

$$\Delta H = AT_D + B \quad (9)$$

where T_D is the dissociation temperature, and A, B are constants given by

$$A = -1050 \text{ J/kg}, \quad B = 3527000 \text{ J/(kgK)}$$

These together with the appropriate equations of balance of mass and heat flow at the dissociation front form the set of governing equations for the gas flow and the pressure and thermal condition in the hydrate reservoir.

In the simulation, the initial length of reservoir, which is 100 m, is divided into 500 grids. That is, a grid spacing of 0.2m is used. To start the computation, it is assumed that a small gas zone around the well is formed with that the dissociation front being at 1m radius. The temperature and pressure profiles in the gas zone at initial time are assumed to be linear.

Equations (1), (6), (7) are three coupled equations governing the temperature and pressure variations in the reservoir. These equations are non-dimensionalized and solved with a finite difference method. An explicit central difference method is used to solve Equation (1) for the pressure and an upwind explicit method is used to solve the convection heat transfer equation in the gas zone given by Equation (6). To solve the conduction-convection heat transfer equation in hydrate zone given by (7), an implicit method is used. Additional details of the computational model is described by Ji et al. (2002).

5 RESULTS

This section presents the numerical solution results for time evolutions of pressure and temperature profiles in the hydrate reservoir under various conditions. In addition, time variations of methane gas production, and location of the dissociation front are also evaluated. The values of the parameter used in the numerical simulation are listed in nomenclature.

For a reservoir temperature of 287 K, reservoir pressure of 15 MPa and a well pressure of 2 MPa, Figure 2 shows variations of pressure and temperature profiles at different times. In this case phase permeabilities in the hydrate and the gas zones are, respectively, 1 md and 8 md. Figure 2a shows that the temperature profiles in the

hydrate and gas zones are quite different. In the hydrate zone, the temperature decreases gradually from reservoir temperature far from the front to the dissociation temperature at the front. In the region near the dissociation front, the gradient of temperature variation becomes sharp, which leads to a sharply increasing heat conduction to the front. In the gas zone, temperature varies very smoothly from the dissociation temperature at the dissociation front to its minimum values at the well. For different times, the temperature profiles from the well to the dissociation front are nearly the same. Figure 2a also shows that the temperature at the dissociation front, T_D , increases gradually with time as the dissociation front moves outward.

The corresponding pressure profiles for different times under the same conditions are presented in Figure 2b. The pressure decreases gradually from the reservoir pressure to the dissociation pressure at the dissociation front, and then decreases in the gas zone. In the region near the well, pressure drops sharply to the well pressure. At the dissociation front, a slope change of pressure profiles is observed, which is due to the large difference of phase permeabilities in the gas zone and hydrate zone in this case.

In Figure 2c, time evolutions of the gas mass flow ($2\pi r\rho v$) across the reservoir is displayed. It is seen that the mass flow is nearly fixed in both the gas zone and the hydrate zone. There is a jump in the mass flow due to the hydrate dissociation, which moves outwards with time as the dissociation front penetrates deeper in the hydrate reservoir. It is also noticed that the gas mass flow in the reservoir and the amount of natural gas generated due to hydrate dissociation increase gradually with time.

Figure 2d presents the heat flow profiles throughout the reservoir at different times. Solid lines in this figure show the profiles at 10 days, while the 40-day profiles are shown by dashed lines. It is seen that in the gas zone, where only the convective heat transfer is considered, the heat flow is nearly the same. In the hydrate zone far from the dissociation front, the heat flow which is primarily convective heat flow is roughly constant. Near the front region, as the temperature decreases sharply to the dissociation temperature at the front, the heat conduction becomes quite large and the total heat flow increases sharply to the maximum value at the dissociation front. There is a jump of heat flow at the dissociation front, which supplies the heat needed for hydrate dissociation. Figure 2d also shows that the total heat flow increases with time.

Comparisons of temperature, pressure and gas flow profiles as predicted by the numerical method used in this paper with the linearization method suggested by

Makogon (Ji et al. 2001) are presented in Figure 3. Here a reservoir temperature of 287 K, a reservoir pressure of 15 MPa and a well pressure of 2 MPa are used and all other parameters are kept identical. In these figures, results of the numerical method are shown by the solid lines, while those of the linearized method are shown by the dashed lines. From Figure 3a, it is seen that both temperature profiles reach the same boundary conditions far from the front, however, near the dissociation front, the temperature profiles of the numerical method have much sharper gradient when compared with that of the linearization method. The reason is that in linearization method suggested by Makogon, the heat conduction was ignored.

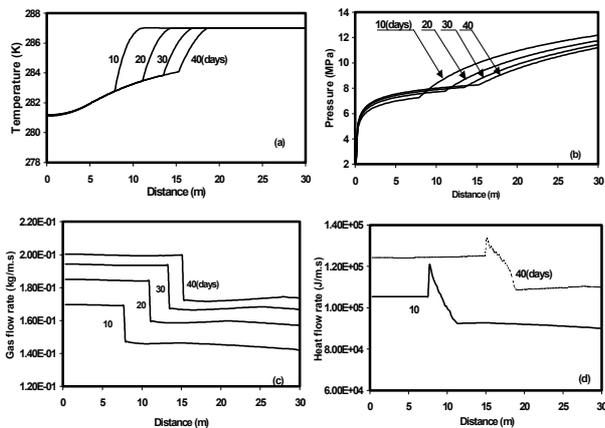


Figure 2. Time variations of pressure, temperature, gas mass flow and heat flow profiles in a reservoir for a well pressure of 2MPa and a reservoir temperature of 287K.

To display the role of various heat flow at the dissociation front, time variations of conductive heat flow into the dissociation front, and convective heat flows in and out of dissociation front are shown in Figure 3b. It is clear that the convective heat flow into the dissociation front is roughly equal to the convective heat flow out of the front. This means that the conductive heat flow plays the dominant role in supplying the heat for hydrate dissociation. Figure 3b further implies that without the heat conduction, the energy balance at the dissociation front cannot be satisfied.

Figure 3c compares the present pressure profiles with those obtained by the linearization method. It is seen that the pressure profiles are qualitatively comparable. Pressure as predicted by the linearization method is lower than that of the numerical method. The main reason is that in the linearization method, Equation (1) is linearized with reservoir pressure P_e in the hydrate zone or well pressure P_G in the gas zone. This leads to the dissociation pressure obtained from the linearization method is lower than that of the numerical method.

Comparison of the mass flow ($2\pi rrv$) profiles as obtained by the numerical and the linearization methods is shown in Figure 3d. It is seen that for both methods, the trends of mass flow profiles throughout the reservoir are similar. However, mass flow of the linearization method is lower than that of the numerical method. The reason is that the velocity as given by Darcy's law is proportional to the pressure gradient, and density is proportional to the ratio of pressure over temperature. At a fixed time, Figure 3 shows that the temperature of the numerical method are higher than that of the linearization method. Furthermore, pressure gradient in the hydrate zone is larger than that of linearization method. The combined effects of a larger pressure gradient and a higher temperature and pressure of the numerical method lead to a higher mass flow throughout the reservoir.

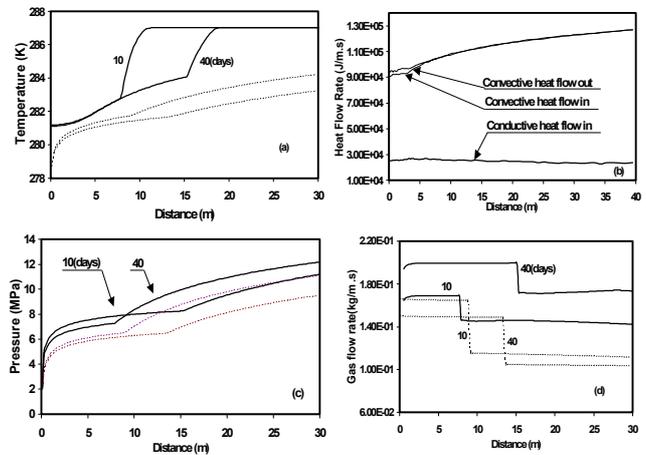


Figure 3. Comparison of the present temperature and pressure profiles and mass flow rate with linearized solutions for a reservoir temperature of 287K and a well pressure of 2MPa. Solid lines: numerical solutions. Dashed lines: linearized solutions suggested by Makogon (Ji et al., 2001).

Time variations of movement of dissociation front, gas mass flow at the well and dissociation temperature for different well pressures as obtained by the present numerical method are compared with those of the linearization approach (Makogon, 1997, Ji et al., 2001) in Figure 4. Here the reservoir conditions are kept fixed at 15 MPa and 287 K. The permeabilities in gas and hydrate zones are, respectively, 8 md and 1 md. In this figure, numerical solutions are shown by solid lines, while the linearized solutions are shown by dashed lines. Figure 4a shows that the distance of the front from the well increases with time. As the well pressure increases, the outward motion slows down. It is observed that for the linearization method, predicts a more sensitive motion of the dissociation front with the well pressure when compared with that of the numerical method.

Time evolutions of the natural gas output are displayed in Figure 4b. For a fixed well pressure and large time the present numerical predicts a large gas

output compared to the linearization method. It is also seen that the natural gas output obtained with numerical method increases with time, and trends to reach a constant value at large time. The gas output as evaluated by the linearization method, however, decreases with time and approaches a constant value at large time.

As was noted before, the present method leads to dissociation temperature and pressure that are functions of time. Figure 4c shows time variations of the dissociation temperature for different well pressures. It is seen that for a fixed well pressure, the dissociation temperature of the numerical method increases with time. (The slight fluctuation of the dissociation temperature at the beginning is related to the assumed initial start up conditions in the reservoir.) The dissociation temperature of the numerical method also varies with the well pressure, and increases as the well pressure increases. For the linearization method, however, the dissociation temperature varies with time very slightly, and is not as sensitive to well pressure to the level that is predicted by the numerical method.

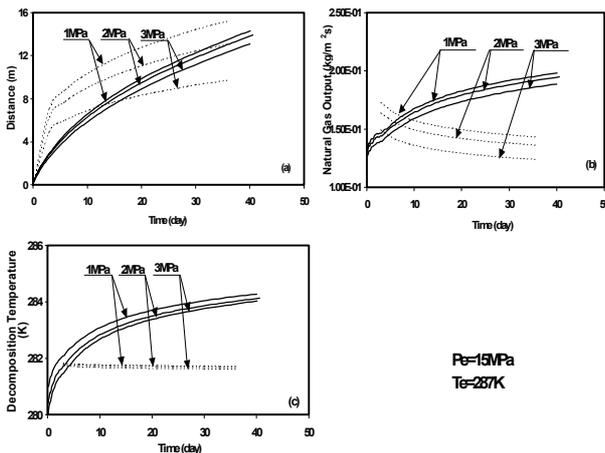


Figure 4. Comparison of present time variations of the position of dissociation front, natural gas output and dissociation temperature with linearized solutions for different well pressures. Solid lines: numerical solutions; Dashed lines: linearized solutions suggested by Makogon (Ji et al., 2001).

For different reservoir temperatures, Figure 5 compares time variations of the movement of the dissociation front, natural gas output and the dissociation temperature as predicted by the numerical method with those of the linearization approach. Here the reservoir and well pressures of 15MPa and 2MPa are assumed and the values of all other parameters are kept the same as those used in Figure 4. Figure 5a shows that the dissociation front moves faster when the reservoir temperature increases. The linearization method, however, predicts a sharper variation of the dissociation front motion when compared with the numerical method.

Figure 5b displays time variations of the natural gas output for different reservoir temperatures. The natural gas output increases with reservoir temperature. The numerical method leads to an increasing trend of natural gas output with time which the linearization approach predicts a decreasing trend. It also observed that the long time natural gas output predicted by the linearization method is lower than that of the numerical method for a fixed reservoir temperature.

Figure 5c shows time variations of the dissociation temperature with the reservoir temperature. The numerical method predicted that the dissociation temperature increases with time and the reservoir temperature. The linearization approach leads to variation of the dissociation temperature.

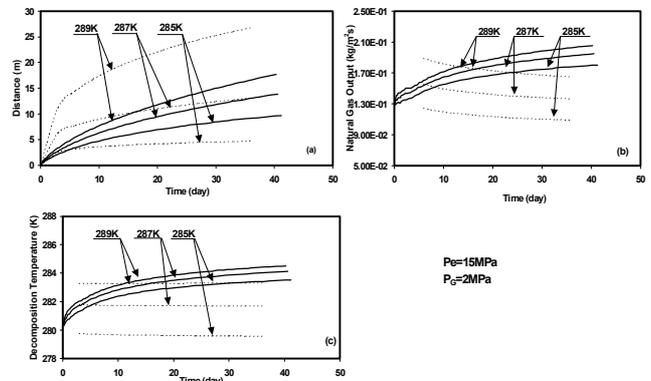


Figure 5. Comparison of the present time variations of the position of dissociation front, natural gas output and dissociation temperature with linearized solutions for different reservoir temperatures. Solid lines: numerical solutions; Dashed lines: linearized solutions suggested by Makogon (Ji et al., 2001).

6 CONCLUSIONS

Natural gas production from hydrate dissociation by a depressuring well is studied. The axisymmetric governing equations for pressure and temperature fields in the reservoir, as well as balance of energy and mass flows at the dissociation front are solved using a finite difference method in conjunction with an iterative scheme. Time evolutions of temperature, pressure, gas mass flow and heat flux profiles across the reservoir, as well the movements of dissociation front and the natural gas output are evaluated. The results are compared with those of the linearization method suggested by Makogon (1997) and Ji et al. (2001). On the basis of the results presented, the following conclusions are drawn:

1. Under favorable conditions, depressurization by a drilling well is a viable method for producing natural gas from a hydrate reservoir.

2. For a fixed reservoir condition, well pressure controls the rate of natural gas output and the motion of the dissociation front. A lower well pressure leads to a higher natural gas output and a faster movement of the dissociation front.
3. The natural gas output and the movement of dissociation front are also sensitive functions of reservoir temperature. When the reservoir temperature increases, the rate of natural gas output increases and the dissociation front moves faster.
4. For a fixed reservoir condition, the dissociation temperature and pressure are slowly varying functions of time.
5. A higher well pressure or a higher reservoir temperature lead to a higher dissociation temperature and pressure.
6. Compared to the linearization method used in Makogon's model, the numerical method introduced in this paper provides a more accurate description for the process of hydrate dissociation.

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8 ACKNOWLEDGEMENT

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