

# Simulation of hydrate dissociation and two phase flow in porous media

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## Abstract

This paper describes a one-dimensional model for hydrate dissociation in porous media by depressurization method. A moving boundary which separates the total simulation zone into two zones is used. The convective-conductive heat transfer and mass transfer in the gas and hydrate zone together with the energy balance at the moving front are analyzed. The system of governing equations is transferred into new coordinate using a coordinate transformation method. Then the numerical method of lines is used to discretize the governing equations after coordinate transformation. Distributions of temperature and pressure for different well pressure and reservoir temperature are presented. It's shown that the speed of the moving front and the gas production rate are sensitive function of the well pressure and the reservoir temperature.

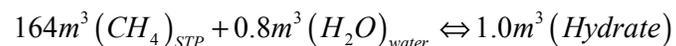
## 1 Introduction

Natural gas hydrates are solid molecular compounds of water with natural gas and there're large amount of methane gas trapped in hydrate reservoirs (Ahmadi, 2004). Natural hydrates occur in two regions: permafrost and under the sea floor. Because the hydrate density is smaller than the density of sea water, the hydrate must cement with the sediment of the sea floor to be stable (Max, 2006). There're three main methods to dissociate the hydrate: depressurization, inhibitor stimulation and thermal stimulation (Ji, 2001). Makogon (1997) proposed a model with analytical solution considering the adiabatic and throttling effects of methane gas together with the gas convective energy. Ji (2001) calculated the undetermined values in Makogon's analytical solution and applied it to a given sets of reservoirs with different operation parameters. Both Makogon and Ji's model neglected the energy balance at the moving front. Ahmadi (2004) used a more general model with both conductive-convective heat transfer and energy balance at the moving front. We followed Ahmadi (2004)'s approach and modified the governing equations to account for the water movement.

## 2 Hydrate dissociation model

Depending on the physical property of the hydrate reservoir, the gas hydrate may exist by itself or coexist with the pressurized gas. We simulated the case that a well is drilled into a hydrate reservoir coexists with methane gas. Depressurization method is used to dissociate the methane hydrate. The depressurization method is the least expensive method of hydrate dissociation and most feasible when the gas hydrate-bearing sands have a large free gas (Max, 2006).

The hydrate decomposition model may be expressed as:



The hydrate will decompose into methane gas and water when the pressure decreases or the temperature rises.

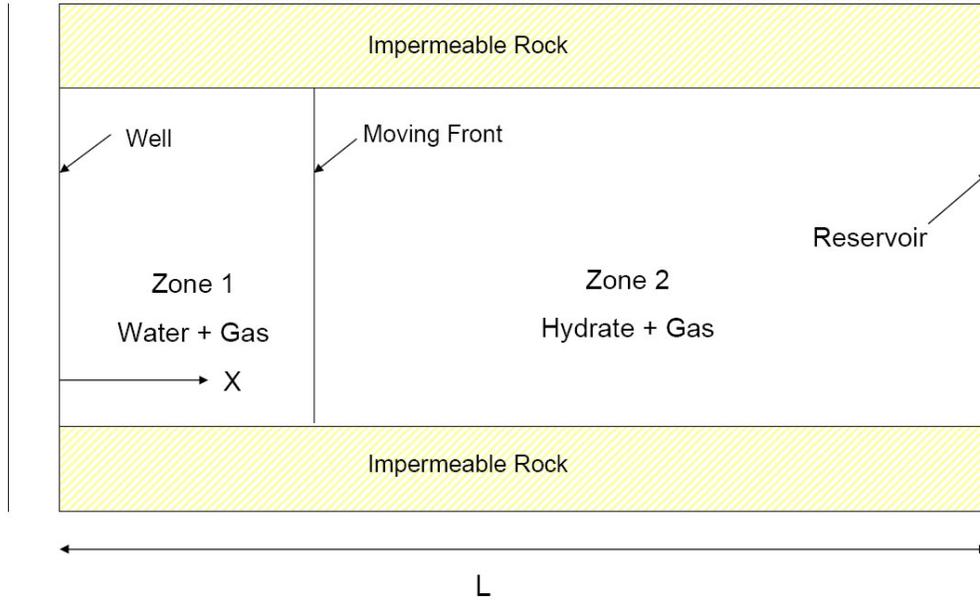


Figure 1 Schematic model for one-dimensional hydrate dissociation in porous media. We assumed that a reservoir of hydrate coexists with gas as shown in Figure 1. Initially, the gas and hydrate coexist at pressure of  $P_e$  (reservoir pressure) and at temperature of  $T_e$  (reservoir temperature).  $P_e$  is higher than the thermodynamic equilibrium pressure of hydrate at  $T_e$ . As soon as a well is drilled into the reservoir and the well pressure is decreased less than the thermodynamic equilibrium pressure for hydrate at the reservoir temperature  $T_e$ , the hydrate will be unstable and begin to dissociate into water and gas near the well. We also assumed that the hydrates dissociate in a small region which is viewed as a moving front. This front separates the entire reservoir into two regions; the dissociated region consists of sand, gas and water and the undissociated region consists of sand, gas and hydrate. The moving front will expand as time passed. The natural gas moves toward the well due to the pressure gradient.

### 3 Governing equations

Our model is similar to Ahmadi (2004)'s model and we modified the equations to include the two phase flow in gas zone while water phase was assumed stationary in Ahmadi's model. We used the concept of relative permeability for the two phase flow. A total length of  $L=100\text{m}$  of hydrate reservoir is simulated in present model.

Continuity equation for water in zone 1:

$$\frac{\partial(\rho_w \phi \alpha)}{\partial t} + \frac{\partial(\rho_w U_w)}{\partial x} = 0 \quad (1)$$

Darcy's law for water velocity in zone 1:

$$U_w = -\frac{K_{absw}K_{rw}}{\mu_w} \frac{\partial P_w}{\partial x} \quad (2)$$

$$K_{rw} = f_{rw}(\alpha) = \alpha^4$$

Here  $K_{absw}$  is the absolute permeability for water of the porous media.  $K_{rw}$  is the relative permeability of water which is a function of the water saturation (Corey, 1994).  $\phi$  is the porosity of the porous media and is assumed to be constant during hydrate dissociation.  $\alpha$  is water saturation and is a variable.  $\rho_w$  is the constant water density.  $\mu_w$  is the viscosity of water and is assumed to be constant.

Continuity equation for gas in zone 1:

$$\frac{\partial(\rho_{g1}\phi(1-\alpha))}{\partial t} + \frac{\partial(\rho_{g1}U_{g1})}{\partial x} = 0 \quad (3)$$

Darcy's law for gas velocity in zone 1:

$$U_{g1} = -\frac{K_{absg}K_{rg}}{\mu_g} \frac{\partial P_{g1}}{\partial x} \quad (4)$$

$$K_{rg} = f_{rg}(\alpha) = (1-\alpha)^4$$

Here  $\mu_g$  is the viscosity of gas and is assumed to be constant during the hydrate dissociation.  $K_{rg}$  is the relative permeability of gas in zone 1 which is a function of the water saturation (Corey,1994).

In equations (2) and(4), the gas pressure and the water pressure is related by

$$P_c = P_{g1} - P_w = f_c(\alpha) \quad (5)$$

In our simulation, the capillary pressure is assumed to be negligible because the value for capillary pressure is relatively small compared to the reservoir pressure.

Energy conservation equation in zone 1 may be written as:

$$\rho_{ave1}C_{pave1} \frac{\partial T_1}{\partial t} + \rho_{g1}C_{pg}U_{g1} \frac{\partial T_1}{\partial x} + \rho_wC_{pw}U_w \frac{\partial T_1}{\partial x} = k_{ave1} \frac{\partial^2 T_1}{\partial x^2} \quad (6)$$

Here  $\rho_{ave1}C_{pave1}$  is the product of the averaged density and averaged heat capacity in zone 1.

$k_{ave1}$  is the averaged heat conductivity.

Continuity equation for gas in zone 2:

$$\phi(1-\beta) \frac{\partial \rho_{g2}}{\partial t} + \frac{\partial(\rho_{g2}U_{g2})}{\partial x} = 0 \quad (7)$$

Darcy's law for velocity in zone 2:

$$U_{g2} = -\frac{K_{absg} K_{effective}}{\mu_g} \frac{\partial P_{g2}}{\partial x} \quad (8)$$

$$K_{effective} = f_{effective}(\beta) = 1 - \beta$$

Here  $\beta$  is saturation of hydrate in zone 2.  $f_{effective}(\beta)$  is a function of  $\beta$  considering the coefficient for the effective permeability in zone 2 due to the existence of hydrate. Energy conservation equation in zone 2 may be written as:

$$\rho_{ave2} C_{pave2} \frac{\partial T_2}{\partial t} + \rho_{g2} C_{pg} U_{g2} \frac{\partial T_2}{\partial x} = k_{ave2} \frac{\partial^2 T_2}{\partial x^2} \quad (9)$$

Here  $\rho_{ave2} C_{pave2}$  is the product of the averaged density and averaged heat capacity in zone 2.

$k_{ave2}$  is the averaged heat conductivity in zone 2.

Mass balance for gas at the moving front:

$$\phi \frac{dS}{dt} (\beta \epsilon \rho_h + (1 - \beta) \rho_{gD} - (1 - \alpha_D) \rho_{gD}) = \rho_{g2} U_{g2} - \rho_{g1} U_{g1} \quad (10)$$

Energy balance at the moving front:

$$\Delta H \rho_h \phi \beta \frac{dS}{dt} = \rho_{g1} C_{pg} T_1 U_{g1} + \rho_w C_{pw} T_1 U_w - k_{ave1} \frac{\partial T_1}{\partial x} - \rho_{g2} C_{pg} T_2 U_{g2} + k_{ave2} \frac{\partial T_2}{\partial x} \quad (11)$$

Here S is the location of the moving front which is a function of time.  $\Delta H$  is the latent heat for hydrate dissociation and is assumed to be constant 458 kJ/kg (Kang, 2001). The latent heat for ice is 333.6 kJ/kg (CRC, 2005). In methane hydrate, the mass fraction of water is about 87 percent. So the latent heat of hydrate and ice should have the same order of magnitude. Thermodynamic equilibrium equation between the gas and the hydrate at the front:

$$\log_{10}(P_D) = 0.0342 (T_D - 273.15) + 0.0005 (T_D - 273.15)^2 + 6.4804 \quad (12)$$

Equation of gas density:

$$\rho_g = \frac{P_g M}{z R T_g} \quad (13)$$

Here M is the molecular weight of methane and R is the universal gas constant. The compressibility z was calculated using the Redlich/Kwong equation of state (Smith, 1996). The calculated value of z is 0.8838 at pressure of 6MPa and temperature of 287K. Although the compressibility z is actually a function of temperature and pressure, we assumed that the compressibility is constant during our simulation for simplicity.

The boundary condition for the water saturation at the moving front is

$$\rho_w \phi \alpha_D = (1 - \epsilon) \rho_h \phi \beta \quad (14)$$

Finally, the initial and boundary conditions are listed below:

$$\begin{aligned}
P_1(0, t) &= P_{well} \\
P_2(x, 0) &= P_2(\infty, t) = P_r \\
P_1(S(t), t) &= P_2(S(t), t) = P_D(T_D) \\
T_2(x, 0) &= T_2(\infty, t) = T_r \\
T_1(S(t), t) &= T_2(S(t), t) = T_D \\
S(0) &= 0
\end{aligned}$$

Here  $P_{well}$  is the gas pressure at the well.  $P_r$  is the gas pressure of the reservoir.  $T_r$  is the temperature of the reservoir.  $P_D$  and  $T_D$  are the pressure and temperature at the moving front respectively. The location of the moving front  $S(t)$  is only a function of time and its initial position is at the well. We transferred the partial differential equations (PDEs) into a new coordinate system so that the moving front is fixed. We then transferred these PDEs to ordinary differential equations (ODEs) using method of lines (Schuesser, 1991). The equations were discretized in space only and kept continuous in time. Our governing equations are stiff and we used MATLAB function ODE15s for stiff problem as the ODE solver to solve our ODEs we got after the coordinate transformation. During the discretization, center difference for pressure term and upwind difference for temperature techniques were used to avoid instability.

#### 4 Results

For all the results shown below, the total simulation length  $L$  is 100 meter, and we begin the dissociation by assuming that at time=0, the moving front already exist and at the length of  $10^{-6} \cdot L = 10^{-4}$  (meter). This is approximation to our assumption of  $S(0) = 0$ . Each zone (1&2) was discretized into 500 intervals. In this section, we first show the results for well pressure of 2MPa, reservoir temperature of 287K and reservoir pressure of 15MPa. We used the averaged heat conductivity and diffusivity for each zone (CRC, 2005). The absolute permeability for gas and water used in this part were 2.4 (milli-Darcy).

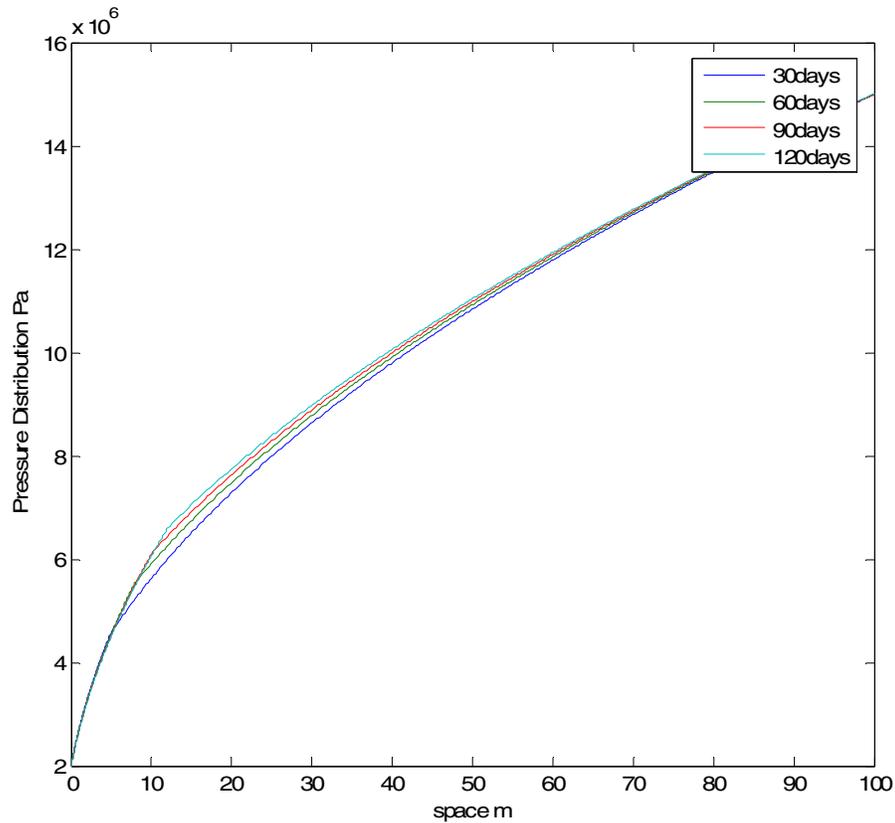


Figure 2 Time variation of pressure in the reservoir for a well pressure of 2MPa and a reservoir temperature of 287K

Figure 2 shows the pressure distribution as a function of time and location during dissociation process. The gas pressure has its maximum value at the reservoir pressure of 15MPa and then decrease to the pressure at the moving front. From the location of the moving front, the gas pressure decrease at a higher rate toward the well pressure of 2MPa. The dissociation pressure at the moving front is increasing with time. This will be further explained in Figure 3.

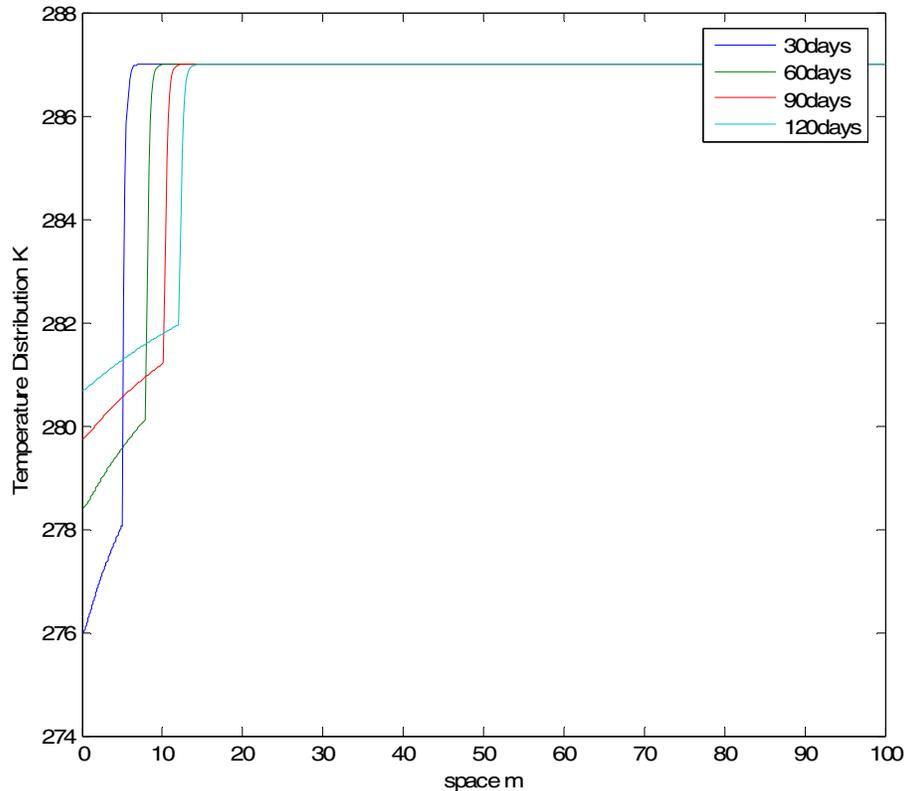


Figure 3 Time variation of temperature in the reservoir for a well pressure of 2MPa and a reservoir temperature of 287K

Figure 3 shows that the temperature also decreases gradually from the reservoir value of 287K to the production well. The temperature close to the reservoir is almost undisturbed. There's a large gradient at the moving front. The reason for this sharp temperature gradient is due to the endothermic reaction of hydrate dissociation. As mentioned before, the depressurization is the least expensive method because no external heat source is needed for hydrate dissociation. All the heat needed for dissociation comes from the reservoir itself. After 30 days, the temperature at the moving front is around 278K while it's 282K after 120days, which means that the dissociation temperature at the moving front will increase with time. The increase of the temperature at the front and well is because of the conductive and convective heat transfer from the reservoir.

## 5 Conclusions

The one dimensional model for hydrate dissociation in porous media has been developed and solved using the numerical coordinate transformation and the numerical method of lines. Based on the results presented in previous sections, the following conclusion may be derived:

1. The methane hydrate can be dissociated by using depressurization method only.
2. A new numerical algorithm applying the coordinate transformation has been shown to be a feasible method and comparable with the analytical solutions.

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