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Heat transfer during the dissociation of hydrate in porous media

Z. Zhang*

Key Laboratory of Mechanics in Fluid Solid Coupling Systems, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

Abstract

The decomposition of gas hydrate accompanied with phase transformation is an endothermic process demanding approximately 52-60 kJ of latent heat per mole of methane in hydrate. Energy is a key factor that restricts the hydrate exploitation. Hence the heat transfer plays a very significant role in the decomposition of hydrate. This paper describes a simple analytical model in cylindrical coordinate for simulating gas production from homogeneous hydrates in porous media by the thermal stimulation method. The results from the analytical solution can predict the temperature distribution in the decomposed and undecomposed hydrate zone, the decomposing interface location at any time, and the rate of the decomposition. This simple model can be used to perform the feasibility of commercial gas production from hydrates reservoirs in the South China Sea region using the warm-seawater at surface. It is of great significance to guide the practical production.

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Keywords: gas hydrate; latent heat; phase transformation; cylindrical coordinate; decomposing interface

Nomenclature

T_l	temperature of liquid region, K ;
T_s	temperature of solid region, K ;
T_i	initial temperature of gas hydrate reservoir, K ;
T_m	decomposition temperature of gas hydrate, K ;
a_l	thermal diffusivity of liquid region, m^2/s ;
a_s	thermal diffusivity of solid region, m^2/s ;
λ_l	thermal conductivity of liquid region, $W/(m \cdot K)$;
λ_s	thermal conductivity of solid region, $W/(m \cdot K)$;

* Corresponding author. Tel.: +86-10-8254-4240-; fax: +86-10-6256-1284.
E-mail address: zhangzhen@imech.ac.cn

Q	line heat source of strength, W/m ;
r	dimension position coordinate, m ;
t	time, s ;
ρ	density, Kg/m^3 ;
L	latent heat of gas hydrate, J/Kg ;
$s(t)$	position of moving interface, m ;
η	parameter.

1. Introduction

Gas hydrates are crystalline solid in which gas molecules are encapsulated inside the lattices of ice crystals under the lower temperature and higher pressure. Under the right temperature and pressure, the amount of gas stored in a given volume of hydrate is 170 times higher than when the gas is at standard conditions. The ice-like gas hydrate which has been found in the permafrost and in deep ocean sediments is a kind of clean-energy and its energy density is ten times larger than that of coal [1, 2]. So gas hydrate is being considered as an alternative energy resource in future. How to explore the immobile and impermeable hydrate is an important problem. The gas hydrates are stable under lower temperature and higher pressure. Once the equilibrium conditions are disturbed, gas will escape from the cage structure. Several ways to decompose gas hydrate include depressurization [3, 4], thermal stimulation [5] and injection of chemicals [6].

Energy is a key factor that restricts the hydrate exploitation. Hence the heat transfer plays a very significant role in the decomposition of hydrate. The decomposition of hydrate is an endothermic process demanding approximately 52-60 kJ of latent heat per mole of methane in hydrate. A huge amount of heat is needed for the massive exploitation of hydrate reservoir. For depressurization and chemical injection methods, the hydrate dissociation energy are provided by the reservoir itself and it is difficult to meet the hydrate decomposition heat demand for using the strata's energy.

The heat-transfer problem involving melting or solidification commonly referred to as “phase-change” or “moving-boundary” problems is important in many engineering applications, such as the making of ice and the freezing of food. The solution of such problems is inherently difficult because the interface between the liquid and solid phases is moving with the latent heat which is absorbed or released at the interface. As a result, the location of the phase-change interface is not known a priori and must follow as a part of the solution. The dissociation of gas hydrate is accompanied by the phase transformation. After decomposition, the solid-state hydrates is decomposed into gas and liquid water. The decomposition of hydrate controlled by the heat flow is analogous with the melting moving boundary problem. This paper describes a simple analytical model in cylindrical coordinate for simulating gas production from homogeneous hydrates in porous media by the thermal stimulation method. To obtain the rate of decomposition controlled by heat transfer, the effect of gas and water flow resulting from the decomposition is ignored and only the heat flow is considered.

2. Mathematical modelling of gas hydrate decomposition with cylindrical symmetry

The gas hydrate decomposition controlled by heat transfer in an infinite medium with cylindrical symmetry is shown in Fig. 1. The gas hydrate is at a uniform temperature T_i , which is lower than the decomposition temperature T_m of the solid phase at the reservoir pressure. A line heat source of strength Q is located at $r=0$. It is assumed that the decomposition starts at the origin $r \rightarrow 0$ at time $t=0$ and the liquid-solid interface moves in the positive r direction. The heat source is activated at time $t=0$ to release heat continuously for time $t > 0$. The problem has cylindrical symmetry and the temperature is unknown in both liquid and solid regions.

The mathematical formulation of this problem is given for the liquid phase as

$$\frac{\partial T_l}{\partial t} = a_l \left(\frac{\partial^2 T_l}{\partial r^2} + \frac{1}{r} \frac{\partial T_l}{\partial r} \right) \quad 0 < r < s(t), \quad t > 0 \quad (1)$$

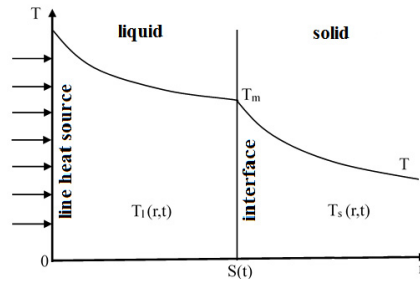


Fig. 1. Diagram of gas hydrate decomposition by a line heat source in an infinite medium with cylindrical symmetry.

for the solid phase as

$$\frac{\partial T_s}{\partial t} = a_s \left(\frac{\partial^2 T_s}{\partial r^2} + \frac{1}{r} \frac{\partial T_s}{\partial r} \right) \quad s(t) < r < \infty, t > 0 \quad (2)$$

$$T_s \Big|_{r \rightarrow \infty} = T_i \quad t > 0 \quad (3)$$

$$T_s \Big|_{t=0} = T_i \quad r > 0 \quad (4)$$

and for the liquid-solid interface as

$$T_l = T_s = T_m \quad r = s(t), t > 0 \quad (5)$$

$$\lambda_s \frac{\partial T_s}{\partial r} - \lambda_l \frac{\partial T_l}{\partial r} = \rho L \frac{ds(t)}{dt} \quad r = s(t), t > 0 \quad (6)$$

We choose the solutions for the liquid and solid phases in the form of [7]

$$T_l = A - BEi\left(-\frac{r^2}{4a_l t}\right) \quad 0 < r < s(t) \quad (7)$$

$$T_s = T_i - CEi\left(-\frac{r^2}{4a_s t}\right) \quad s(t) < r < \infty \quad (8)$$

According to the boundary condition and initial condition, when $\frac{s^2(t)}{4a_l t} = \eta^2$ is introduced, the solutions for the temperature in the liquid and solid phases become

$$T_l = T_m + \frac{Q}{4\pi\lambda_l} \left[Ei(-\eta^2) - Ei\left(-\frac{r^2}{4a_l t}\right) \right] \quad 0 < r < s(t) \quad (9)$$

$$T_s = T_i - \frac{T_i - T_m}{Ei(-\eta^2 \frac{a_l}{a_s})} Ei(-\frac{r^2}{4a_s t}) \quad s(t) < r < \infty \tag{10}$$

Finally, substituting equations (9) and (10) into the interface energy-balance equation (6), the following transcendental equation is obtained for the determination of η .

$$-\lambda_s \frac{(T_i - T_m)}{Ei(-\eta^2 \frac{a_l}{a_s})} \exp(-\eta^2 \frac{a_l}{a_s}) + \frac{Q}{4\pi} \exp(-\eta^2) = \rho L a_i \eta^2 \tag{11}$$

Once the η is known, the location of the solid-liquid interface is determined by $\frac{s^2(t)}{4a_s t} = \eta^2$, and the temperature of the liquid and solid phases is determined by equations (9) and (10) respectively.

3. Results and discussion

According to previous exploration data, gas hydrate is rich in South China Sea Area. It is estimated that the amount of natural gas hydrate in this area may add up to 70 billion ton. The South China Sea region is located in the tropics where the temperature of the surface water is about 25 ~ 30 °C. Although the heat flux density of seawater is low, the total thermal energy is considerable for the large quantity of seawater. This simple model can be used to perform the feasibility of commercial gas production from hydrates reservoirs in the South China Sea region by using the warm-seawater at surface. It is of great significance to guide the practical production.

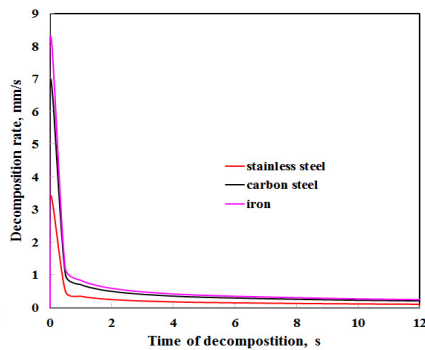
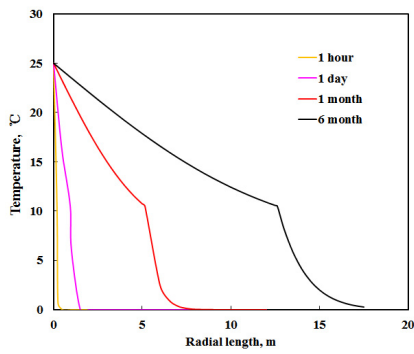


Fig. 2. Temporal and spatial distribution of the temperature Fig. 3. Decomposition rate for different material pipeline

The results from the analytical solution can predict the temperature distribution in the decomposed and undecomposed hydrate zone, the decomposing interface location at any time, and the rate of the decomposition. Figure 2 is the temporal and spatial distribution of temperature. When the hot water is injected into the pipelines, which pass through the hydrate reservoir, the hydrate zone near the thermal pipe firstly decomposes. With a steady stream of heat injection, more and more hydrate starts to decompose and the decomposing interface location moves forward gradually. The thermal conductivity changes with the materials. Here are three kinds of pipelines that are used to simulate, see Fig.3. The thermal conductivity of iron is 73.27 W/ (m · K), which is the largest. So the decomposition rate of iron pipe is larger than that of stainless steel pipe and carbon steel pipe. It can be seen that the

decomposition rate reaches the maximum at the start, and then rapidly decreases with the increase of decomposition time.

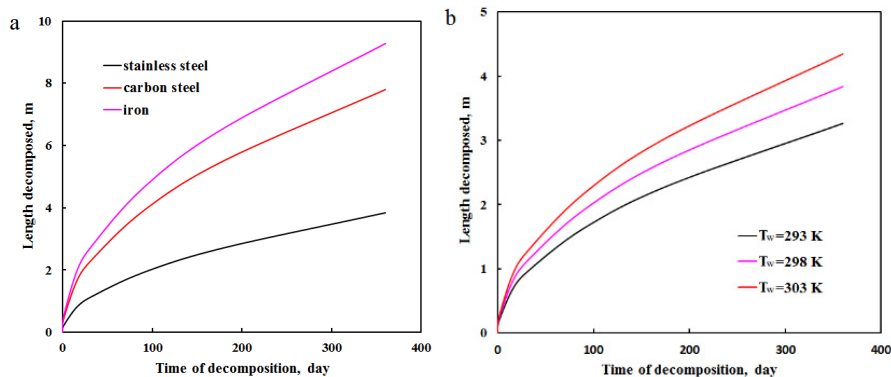


Fig. 4. Location of the decomposition front (a) for different material; (b) for different value of injected water temperature.

Figure 4(a) shows the effect of different material pipes on the decomposition front. Due to the thermal conductivity of irons is the largest, heat is transferred more rapidly than the other two kinds of pipes. So the length of decomposition using irons pipes is longer than the others. Figure 4(b) describes the effect of injected water with different temperature on the decomposition front. The higher the temperature of the injected water is, the longer the decomposition length will be.

The effects of gas and water flow are ignored in the simple analytical model established in this paper. In the next work, we'll establish a complete mathematical model coupling heat transfer and fluid flow to simulate the production of gas hydrates numerically.

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