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# A theoretical model for predicting the spatial distribution of gas hydrate dissociation under the combination of depressurization and heating without the discontinuous interface assumption

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ABSTRACT

Spatial distribution of gas hydrate dissociation is essential in analyzing gas recovery and related potential hazards. This work develops a 1D model for predicting the spatial distribution of gas hydrate dissociation under the combination of depressurization and heating in the clay-silty sediments. Without assuming a discontinuous interface and a sudden decrease of pressure, the sediment is divided into a dissociated zone, a dissociating zone, and an undissociated zone. The dissociating zone is further separated into a heating subzone and a non-heating subzone. This work finds that (i) the thicknesses of the dissociating zone and the heating subzone as well as the propagation distance of the hydrate dissociation front are all linear with the square root of time, and the square root of hydrate dissociation time at any location is also linear with the distance between the location and the production well; (ii) the expansion velocity of the dissociating zone is about ninety times faster than that of the heating subzone, and a higher absolute permeability causes a faster expansion velocity of the dissociating zone, but barely affects the expansion velocity of the heating subzone; and (iii) the thickness of the heating subzone is less than 5% of the thickness of the dissociating zone in the latter stage of the hydrate dissociation process.



## 1. Introduction

Gas hydrates (GH) as a source of natural gas exist in the form of ice-like crystals composed of gas and water and are stored in seabed sediments along the continental margin and permafrost regions (Sloan and Koh, 2007). GH dissociation, a phase transition from solid to liquid and gas, may result in dramatical changes of petrophysical, geophysical, and geochemical properties of hydrate-bearing sediments (HBS) during gas recovery from GH (Waite et al., 2009). Therefore, it is of great importance to have a thorough understanding of the spatial distribution of GH dissociation in sediments, size of the dissociation region and location of the dissociation front in particular (Morikami et al., 2008; Anderson et al., 2008; Ikegami et al., 2008; Primiero et al., 2008). Proposed methods for gas recovery mainly include depressurization, thermal stimulation, inhibitor injection and their combinations (Lee and Holder, 2001; Klauda and Sandler, 2005; Sloan and Koh, 2007; Demirbas, 2010), among which the combination of depressurization and heating is the most promising one (Henninges et al., 2005; Moridis et al., 2009; Bai and Li, 2010; Yang et al., 2012).

GH dissociation in HBS is a physical–chemical process including conductive and convective heat transfer, two-phase fluid flow in pores, and intrinsic kinetics of GH dissociation, and its mathematical models normally consist of equations of energy conservation and mass balance along with the intrinsic kinetics of GH dissociation. A number of one-dimensional (1D) analytical models were presented to predict the location of the hydrate dissociation front (HDF) by assuming that GH dissociation happens instantaneously at a discontinuous interface which divides HBS into an undissociated zone and a dissociated zone (Selim and Sloan, 1989; Yousif et al., 1990; Goel et al., 2001; Ji et al., 2001; Tsypkin, 2001; Hong and Pooladi-Darvish, 2003). However, detailed investigations showed that GH dissociation occurs throughout the undissociated zone because the pressure decrease propagates from the boundary into the undissociated zone (Hong and Pooladi-Darvish, 2005; Moridis and Kowalsky, 2006). Then Gerami and Pooladi-Darvish (2007) presented a 1D analytical model

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**Nomenclature**

| | |
|---|---|
| $a$ | constant, Pa |
| $a_1$, $a_2$, $a_3$ | dimensionless group parameters |
| $A_s$ | area of hydrate dissociation per unit volume, $m^{-1}$ |
| $b$ | dimensionless constant |
| $b_1$, $b_2$ | dimensionless group parameters |
| $c$ | constant, K |
| $c_1$ | dimensionless group parameters |
| $C$ | specific heat capacity, J/kg K |
| $C_0$ | constant, J/kg K |
| $d_1$, $d_2$, $d_3$, $d_4$ | dimensionless group parameters |
| $\Delta E$ | active energy for hydrate dissociation, J/mol |
| $H$ | thickness of hydrate-bearing sediment, m |
| $H_0$ | constant, J/kg |
| $\Delta H$ | heat of hydrate dissociation, J/kg |
| $k_d$ | hydrate dissociation rate constant, kg/m$^2$ Pa s |
| $k_r$ | relative permeability |
| $k_0$ | intrinsic dissociation rate constant, kg/ m$^2$ Pa s |
| $K$ | absolute permeability of hydrate-bearing sediment, m$^2$ |
| $K_0$ | absolut permeability of sediment without hydrate (intrinsic absolute permeability), m$^2$ |
| $L$ | length of hydrate-bearing sediment, m |
| $\dot{m}_g$ | local mass rate of gas produced by GH dissociation per unit volume, kg/m$^3$ s |
| $\dot{m}_h$ | local mass rate of GH dissociated per unit volume, kg/m$^3$ s |
| $\dot{m}_w$ | local mass rate of water produced by GH dissociation per unit volume, kg/m$^3$ s |
| $M$ | molecular weight, kg/mol |
| $n_c$ | dimensionless constant |
| $n_g$ | dimensionless constant |
| $n_w$ | dimensionless constant |
| $N$ | reduction coefficient |
| $N_H$ | hydration number |
| $p_c$ | capillary pressure, Pa |
| $p_c^e$ | entry pressure, Pa |
| $P$ or $p$ | pressure, Pa |
| $P_{well}$ | pressure in the production well, Pa |
| $R$ | universal gas constant (=8.314 J/mol K) |
| $S$ | saturation |
| $S_{gr}$ | residual gas saturation |
| $S_{wr}$ | immobile water saturation |
| $t_{gs}$ | characteristic time of gas flow in pores, s |
| $t_{hc}$ | characteristic time of heat conduction, s |
| $t_{ws}$ | characteristic time of water flow in pores, s |
| $t^*$ | characteristic time of intrinsic kinetic of hydrate dissociation, s |
| $t_0$ | characteristic time for dimensionless analysis (=$t_{hc}$), s |
| $\Delta t_{SH}$ | hydrate dissociation time at any location, s |
| $T$ | temperature, K |
| $T_{heat}$ | temperature in the production well, K |
| $U$ | darcy velocity, m/s |
| $x$ | patial variable along hydrate-bearing sediment, m |
| $x_{PRe}$ | propagation distance of the pressure decrease front, m |
| $x_{sub}$ | length of the heating subzone, m |
| $x_{TRe}$ | propagation distance of the temperature decrease front, m |
| $x_{TRi}$ | propagation distance of the temperature increase front, m |
| $x_{\mathrm{I}}$ | length of the dissociated zone (Zone I), m |
| $x_{\mathrm{II}}$ | length of the dissociating zone (Zone II), m |
| $x^*$ | propagation distance of the heat conduction front in the time of $t_0$, m |
| $x_0$ | characteristic length for dimensionless analysis (=$L$), m |
| $\Gamma$ | dimensionless group parameter |
| $\Theta$ | dimensionless group parameter |
| $\lambda$ | thermal conductivity, J/m K |
| $\mu$ | viscosity coefficient, Pa s |
| $M_\Pi$ | matrixes of dimensionless group parameters |
| $M_D$ | matrixes of dimensionless group parameters |
| $\xi$ | dimensionless spatial variable |
| $\Pi_1$ | dimensionless group parameter (=1) |
| $\Pi_2$ | dimensionless group parameter, indicating the ratio of the characteristic time of heat conduction to that of gas flow in pores |
| $\Pi_3$ | dimensionless group parameter, indicating the ratio of the characteristic time of heat conduction to that of water flow in pores |
| $\Pi_4$ | dimensionless group parameter, indicating the ratio of the characteristic time of heat conduction to that of intrinsic kinetic of hydrate dissociation |
| $\rho$ | density, kg/m$^3$ |
| $\tau$ | dimensionless time |
| $\varphi$ | porosity |
| $\varphi_{wg}$ | effective porosity occupied by gas and water |
| $\Psi_{PRe}$ | slope of the line of the dimensionless propagation distance of the pressure decrease front changing with the square root of the dimensionless time |
| $\Psi_{TRe}$ | slope of the line of the dimensionless propagation distance of the temperature decrease front changing with the square root of the dimensionless time |
| $\Psi_{TRi}$ | slope of the line of the dimensionless propagation distance of the temperature increase front changing with the square root of the dimensionless time |
| $\Psi_{SH}$ | slope of the line of the square root of the dimensionless hydrate dissociation time at any location changing with the dimensionless distance between the location and the production well |

*Subscripts and superscripts*

| | |
|---|---|
| $D$ | dimensionless |
| $eq$ | equilibrium condition |
| $g$ | gas |
| $h$ | hydrate |
| $i$ | indicator |
| $s$ | sand |
| $w$ | water |
| 0 | initial condition |

incorporating conductive heat transfer and intrinsic kinetics of GH dissociation to evaluate the gas production rate. Their model, without the discontinuous interface assumption, assumed that GH decomposes anywhere inside the undissociated zone when the equilibrium state is destroyed by a sudden decrease of pressure. But in the clay-silty sediments in Shenhu Area of South China Sea, the pressure decreases only gradually due to the low absolute permeability of HBS (Su et al., 2012).

In order to predict the spatial distribution of GH dissociation under the combination of depressurization and heating in the