

HYDRATE DISSOCIATION IN A 1-D DOMAIN

I. Domain Description

1-D Cartesian system, $L \times W \times H = 1.5 \text{ m} \times 1.0 \text{ m} \times 1.0 \text{ m}$

Discretization: $30 \times 1 \times 1$ in (x, y, z)

Uniform $\Delta x = 0.05 \text{ m}$ each; $\Delta y = \Delta z = 1 \text{ m}$

II. Initial Conditions

Pressure: $P_i = 8 \text{ MPa}$

Temperature: $T_i = 2 \text{ }^\circ\text{C}$ (for thermal stimulation), $T_i = 6 \text{ }^\circ\text{C}$ (for depressurization)

Saturations: $S_H = 0.5, S_A = 0.5, S_G = 0.0$

III. Boundary Conditions

At $x = X_{max}$: No mass or heat flow

At $x = 0$: Constant $S_A = 1.0$

(1) Constant $P_0 = P_i$
Constant $T_0 = 45 \text{ }^\circ\text{C}$
Thermal stimulation

(2) Constant $T_0 = T_i = 6 \text{ }^\circ\text{C}$
Constant $P_0 = 2.8 \text{ MPa}$
***Depressurization to a pressure above the Q-point,
no ice formation***

(3) Constant $T_0 = T_i = 6 \text{ }^\circ\text{C}$
Constant $P_0 = 0.5 \text{ MPa}$
***Depressurization to a pressure below the Q-point,
leading to ice formation***

IV. Medium Properties

Hydraulic Properties

Intrinsic permeability: $k = 3.0 \times 10^{-13} \text{ m}^2$ (0.3 Darcys)

Porosity: $\phi = 0.3$

Pore compressibility: $\beta = 5.0 \times 10^{-9} \text{ Pa}^{-1}$

Grain density: $\rho_R = 2600 \text{ kg/m}^3$

Thermal Properties

Grain specific heat: $C = 1000 \text{ J/kg/K}$

Dry thermal conductivity: $k_{\theta D} = 2 \text{ W/m/K}$

Wet thermal conductivity: $k_{\theta W} = 2.18 \text{ W/m/K}$

Composite thermal conductivity model: Linear (per earlier decision)

$$k_{\theta} = k_{\theta D} + \phi (S_A k_{\theta w} + S_H k_{\theta H} + S_I k_{\theta I} + S_G k_{\theta G}) \quad (1)$$

where the subscripts w, H, I, G denote water, hydrate, ice and gas, respectively.

Note: This k_{θ} model will result in a thermal conductivity that is about 70% of the composite k_{θ} of hydrate-bearing sediments measured in lab and field experiments.

V. Relative Permeability

The treatment and description of the wettability properties is likely to be an early departure point of the various models in the study because of differences in the models and in the approach.

Relative permeability model: *Stone [1970] + Aziz [1979]*

$$k_{rG} = (S_G^*)^n, \quad S_G^* = (S_G - S_{irG}) / (I - S_{irA}) \quad (2)$$

$$k_{rA} = (S_A^*)^n, \quad S_A^* = (S_A - S_{irA}) / (I - S_{irA}) \quad (3)$$

where the subscripts irG, irA denote aqueous and gas phase irreducible saturations, respectively. For this problem:

$$n = 3.0$$

$$S_{irA} = 0.12$$

$$S_{irG} = 0.02$$

Note: We are not proposing the Mualem/vanGenuchten/Parker relative permeability functions because these cannot handle non-zero irreducible gas saturations. In a previous communication, we have sent tables of the relative permeability values as a function of saturation.

Effect of Solid (=Hydrate) Phase

Original Porous Medium (OPM) model: It is based on the treatment of (a) the medium porosity as unaffected by the emergence of hydrates and/or ice (although subject to change due to changes in pressure and temperature), (b) of the intrinsic permeability of the porous media as unchanging during the evolution of the solid phases, and (c) of the fluid flow as a relative permeability issue controlled by the saturations of the various phases in the pores.

VI. Capillary Pressure

Capillary pressure type and parameters in this simulation

The capillary pressure function used in problems #1 and #2 of the code comparison study were used in this simulation. The parameters for this vanGenuchten-type function were listed in earlier communications by White and McGrath. **Note that, to maintain consistency with the relative permeability function, $S_{irA} = 0.11$ in the capillary pressure function.** Additionally, scaling consistent with the OPM model was also used. Although an effort was made to be as close as possible to the values used by White and McGrath, the OPM scaling will result in different capillary pressures than those computed in the other codes.

Background Information

The role of capillary pressure seems to be of critical importance, especially in Class 1 hydrate formations. It is almost certain that this will be a major departure point for the codes. For simplicity, we can assume $P_{cap} = 0$ for this problem. This will eliminate potential problems of capillary pressure model availability in the various codes.

If a non-zero P_{cap} is desired, we can use an appropriately scaled P_c function (to account for the presence of the solid phases) based on the vanGenuchten (1981) model:

$$P_{cap} = -P_0 \left[(S^*)^{-1/\lambda} - 1 \right]^\lambda, \quad S^* = \frac{(S_A - S_{irA})}{(S_{mxA} - S_{irA})} \quad (4)$$

subject to the restriction: $-P_{max} \leq P_{cap} \leq 0$

Parameters: $\lambda = 1 - 1/n = 0.45$
 $S_{irA} = 0.11$ (chosen slightly smaller than the corresponding parameter in the relative permeability function)
 $1/P_0 = \alpha/\rho_w g = 8.0 \times 10^{-5} \text{ Pa}^{-1}$
 $P_{max} = 5.0 \times 10^6 \text{ Pa}$
 $S_{mxA} = 1$

The simplest capillary pressure scaling involves adjustments of fluid saturations to reflect the changing solid matrix. We represent *active* solids (i.e. ice that may melt or hydrate that may dissociate, as opposed to solid minerals which are inert) by means of a *solid saturation*, denoted by $S_S = S_H + S_I$, which measures the fraction of active pore space occupied by solids. The fraction of pore space available to fluid phases is $S_A + S_G$, and we have the constraint

$$S_A + S_G = 1 - S_S \quad (5)$$

Let $P_{cap,0}$ denote the capillary pressure function applicable to a porous medium free of solid saturation ($S_S = 0$) with porosity ϕ_0 . The active porosity available to fluid is then

$$\phi = (S_A + S_G) \phi_0 \Rightarrow \frac{\phi}{\phi_0} = (S_A + S_G) \quad (6)$$

We measure liquid saturation on a scale that refers to total *active* (fluid plus hydrate- and ice-filled) pore space ϕ_0 in the ice-free porous medium. An aqueous saturation S_A in the medium with solid saturation S_S then corresponds to a saturation

$$S_A^* = \frac{S_A}{S_A + S_G} \quad (7)$$

relative to fluid-filled pore space, and this is the value to be inserted in the r.h.s of equation (4) instead of S_A .

Based on theoretical analysis, further scaling may be necessary to describe the capillary pressure in hydrate-bearing media. Examining a variety of unconsolidated media, *Leverett* [1941] determined a dependence of capillary pressure on permeability and porosity, as follows:

$$P_{cap}(S_A) = \sqrt{\frac{k_0}{k} \cdot \frac{\phi}{\phi_0}} P_{cap,0} \quad (8)$$

where k_0 and ϕ_0 are permeability and porosity, respectively, of the porous medium whose capillary pressure function is $P_{cap,0}$. The argument in the capillary pressure function $P_{cap,0}$ on the r.h.s of Equation (8) is the adjusted liquid (aqueous) saturation given by equation (7).

In computing P_{cap} from equation (8), the porosity ratio is described by equation (6). There are several options in estimating the ratio of permeabilities with and without solid phases present. The simplest estimate of the ‘new’ absolute permeability of the medium can be given by *Moridis et al.* [2005] as

$$\frac{k}{k_0} = \frac{1}{2} [k_{rA}(S_A = 1 - S_S) + k_{rG}(S_G = 1 - S_S)] \quad (9)$$

VII. Data and Sampling Frequency

Data to be compared

Pressure, temperature, phase saturations, phase relative permeabilities, capillary pressure, mass fraction of CH₄ in the aqueous phase, cumulative CH₄ release rate from the entire domain, rate of CH₄ production at the $x = 0$ boundary, cumulative volume of released CH₄, cumulative volume of produced CH₄ at the $x = 0$ boundary, heat flows through the $x = 0$ boundary

For thermal stimulation

Results to be reported at 1 hr, 3 hrs, 6 hrs, 12 hrs, 1 day, 2 days, 3 days, 5 days

For depressurization to P above the Q -point

Results to be reported at 2 min, 5 min, 20 min, 1 hr, 1.5 hrs, 12 hrs, 1 day, 2 days, 3 days

For depressurization to P below the Q -point

Results to be reported at: 2 min, 5 min, 10 min, 20 min, 30 min, 45 min, 1 hr, 1 day, 5 days