RELATIVE PERMEABILITY CURVES DURING HYDRATE DISSOCIATION IN DEPRESSURIZATION

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ABSTRACT
Depressurization is thought to be a promising method for gas recovery from methane hydrate reservoirs, but considerable water production is expected when this method is applied to the hydrate reservoir of high initial water saturation. In this case, the prediction of water production is a critical problem. This study examined relative permeability curves during hydrate dissociation by comparing numerical simulations with laboratory experiments. Data of gas and water volumes produced during depressurization were taken from gas recovery experiments using sand-packed cores containing methane hydrates. In each experiment, hydrates were dissociated by depressurization at a constant pressure. The surrounding temperature was held constant during dissociation. The volumes of gas and water produced, the temperatures inside of the core, and the pressures at the both ends of the core were measured continuously. The experimental results were compared with numerical simulations by using the simulator MH21-HYDRES (MH21 Hydrate Reservoir Simulator). The experimental results showed that considerable volume of water was produced during hydrate dissociation, and the simulator could not reproduce the large water production when we used typical relative permeability curves such as the Corey model. To obtain good matching for the volumes of gas and water produced during hydrate dissociation, the shape of relative permeability curves was modified to express the rapid decrease in gas permeability with increasing water saturation. This result suggests that the connate water can be easily displaced by hydrate-dissociated gas and move forward in the hydrate reservoir of high initial water saturation.

Keywords: methane hydrate, gas production, depressurization, relative permeability

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NOMENCLATURE
C Specific heat [J·kg\(^{-1}\)·K\(^{-1}\)]
D Depth from a reference level [m]
g Acceleration of gravity [9.80665 m\(^2\)·s\(^{-2}\)]
h Enthalpy [J·kg\(^{-1}\)]
k\(_D\) Absolute permeability [m\(^2\)]
k\(_{D0}\) Absolute permeability at S\(_H\)=0 [m\(^2\)]
kr\(_l\) Relative permeability to phase (l) [fraction]
N Permeability reduction index
N\(_g\) Index of gas relative permeability
N\(_w\) Index of water relative permeability
in\(_&\) Net generation rate of component (i) per 1m\(^3\) of sediment during hydrate dissociation /formation and water freezing/ice melting process (i = CH\(_4\), H\(_2\)O) [mol·s\(^{-1}\)·m\(^{-3}\)]
\(\dot{n}_{\text{dissoc},i}\) Generation rate of component (i) due to hydrate dissociation per 1m\(^3\) of sediment (i = CH\(_4\), H\(_2\)O) [mol·s\(^{-1}\)·m\(^{-3}\)]
\(\dot{n}_{\text{prod},l}\) Production rate of phase (l) per 1m\(^3\) of sediment [mol·s\(^{-1}\)·m\(^{-3}\)]
p pressure [Pa]
\(\dot{Q}_H\) Heat sink rate due to hydrate dissociation per 1m\(^3\) of sediment [W·m\(^{-3}\)]
\(\dot{Q}_r\) Heat sink rate with ice-water phase transition per 1m\(^3\) of sediment [W·m\(^{-3}\)]
\(\dot{Q}_{\text{salts}}\) Heat generation rate with salt dissolution into water per 1m\(^3\) of sediment [W·m\(^{-3}\)]
\(\dot{Q}_\text{ext}\) Heat sink rate to outside at the system boundary per 1m\(^3\) of sediment [W·m\(^{-3}\)]
\(\dot{Q}_{\text{prod},l}\) Heat sink rate with production of phase (l) per 1m\(^3\) of sediment [W·m\(^{-3}\)]
S\(_t\) Saturation of phase (l) [fraction]
S\(_{iw}\) Irreducible water saturation [fraction]
S\(_{rg}\) Residual gas saturation [fraction]
S\(_{w,m}\) Effective water saturation [fraction]
T Temperature [K]
t Time [s]
U Internal energy [J kg\(^{-1}\)]
x\(_i\) Mole fraction of component (i) in water phase (i = MeOH, salts) [fraction]
\(\phi\) Porosity [fraction]
\(\lambda_{\text{eff}}\) Effective thermal conductivity of sediment, [W·m\(^{-1}\)·K\(^{-1}\)]
\(\mu\) Viscosity [Pa·s]
\(\bar{\rho}\) Mass density [kg·m\(^{-3}\)]
\(\rho\) Molar density [mol·m\(^{-3}\)]

Subscripts
g Gas phase
H Hydrate phase
I Ice phase
R Sand grain (rock matrix)
w Water phase

INTRODUCTION
Methane hydrate is a crystalline solid composed of water and methane. The total amount of methane gas in this solid form may surpass the total conventional gas reserve and some individual methane hydrate accumulations may contain significant and concentrated resources [1]. That indicates the potential as a future energy resource. Depressurization is a promising method for gas production from methane hydrate reservoirs, both from economic and ecological perspectives. But, in the hydrate reservoir of high initial water saturation, considerable water production may become a problem of application of the method. So the prediction of water production is one of the most important issues. In this study, numerical simulations were done using the original developed simulator: MH21-HYDRES (MH21 Hydrate Reservoir Simulator) [2] to examine relative permeability curves during hydrate dissociation by comparing numerical simulations with laboratory experiments.

THEORY OF SIMULATOR
Governing equations
The MH21-HYDRES is a compositional simulator solving the equations of mass balances for methane, water, methanol and salts, and one energy balance equation. The mass and energy balances equations are as follows:

Mass balance equations:
For methane components:
\[
\nabla \cdot \left( k\_D \cdot \frac{k\_rg \cdot p\_g}{\mu\_g} (\nabla p\_g - \bar{\rho}\_g \cdot g \nabla D) \right) + \dot{n}\_CH\(_4\) - \dot{n}\_prod,g
\]
\[
= \frac{\partial}{\partial t} (\rho\_g \cdot \phi \cdot S\_g)
\]
(1)

For water components:
\[
\nabla \cdot \left( k\_D \cdot \frac{k\_rw \cdot p\_w (1 - x\_MeOH - x\_salts)}{\mu\_w} (\nabla p\_w - \bar{\rho}\_w \cdot g \nabla D) \right) + \dot{n}\_H\(_2\)O (1 - x\_MeOH - x\_salts) \dot{n}\_prod,w
\]
\[
= \frac{\partial}{\partial t} (\rho\_w \cdot \phi \cdot S\_w (1 - x\_MeOH - x\_salts))
\]
(2)
For methanol components:
\[
\nabla \left( \frac{k_p k_m w x_{MeOH}}{\mu_w} (\nabla p_w - \rho g \nabla D) \right) - x_{MeOH} \hat{n}_{prod,w} = \frac{\partial}{\partial t} \left( \phi \rho g x_{MeOH} S_w \right)
\]
(3)

For salts components:
\[
\nabla \left( \frac{k_p k_m w x_{salts}}{\mu_w} (\nabla p_w - \rho g \nabla D) \right) - x_{salts} \hat{n}_{prod,w} = \frac{\partial}{\partial t} \left( \phi \rho g x_{salts} S_w \right)
\]
(4)

Energy balance equation:
\[
\frac{\partial}{\partial t} \left\{ (1 - \phi) \rho C_r T + \rho \left( \sum_{i=1}^{i=M, salts} S_i \rho C_r T + \sum_{i=w,g} S_i \rho U_i \right) \right\} = \nabla \cdot (\lambda_{eff} \nabla T) + \nabla \cdot \left( \sum_{i=w,g} h_i k_{i,m} k_{m,w} \frac{\rho}{\mu_i} (\nabla p_i - \rho g \nabla D) \right) - \dot{Q}_w - \dot{Q}_v - \dot{Q}_{salts} - \dot{Q}_{w_s} + \sum_{i=prod} \dot{Q}_{i}
\]
(5)

**Permeability reduction in porous media containing hydrates**

The permeability of hydrate reservoirs can change due to presence of hydrates. Masuda et al. have proposed a following model to express this phenomenon [2]. Figure 1 shows the permeability reduction ratio. The permeability reduction index N is an empirical parameter. In this study, N was set as 2.

\[
k_p = k_{p,0} \left( 1 - S_H \right)^N
\]
(6)

![Figure 1 Permeability reduction ratio vs. S_H.](image)

**Relative permeability curves**

Two different relative permeability models were used for comparison studies. One model is Corey model [3] typically used in a conventional reservoir simulation. The other model was derived from Kozeny-Carman model [4]. In the model derived from Kozeny-Carman model, we assumed that hydrates occupy the capillary walls and gas/water flows the center of capillaries. Through comparison studies between experiments and simulations, the shape of relative permeability derived from Kozeny-Carman model was modified. These relative permeability models are as follows:

**Corey model:**

Gas relative permeability is modeled as follow:

\[
k_{rg} = \left\{ \frac{1 - S_{rg} - S_{w,m}}{1 - S_{rg} - S_{w}} \right\}^{1 - n} \left\{ 1 - \left( \frac{S_{w,m} - S_{w}}{1 - S_{rg} - S_{w}} \right)^n \right\}^{n-1}
\]
(7)

Water relative permeability is modeled as follow:

\[
k_{rw} = \left\{ \frac{0}{1 - S_{rg} - S_{w}} \right\}^4 \left\{ S_{w,m} - S_{w} \right\}^{1 - n} \left\{ 1 - S_{rg} - S_{w} \right\}^{-n}
\]
(8)

In this study, residual gas saturation was set as 0.1 and irreducible water saturation was set as 0.2.

The model derived from Kozeny-Carman model:

Gas relative permeability is modeled as follow:

\[
k_{rg} = \left\{ \frac{0}{1 - S_{rg} - S_{w}} \right\}^4 \left\{ S_{w,m} - S_{w} \right\}^{1 - n}
\]
(9)

Water relative permeability is modeled as follow:

\[
k_{rw} = S_{w,m}^n
\]
(10)

Theoretically, \(N_g\) and \(N_w\) are 1 and 2 respectively. In this study, \(N_g\) and \(N_w\) were used as matching parameters for gas and water production.
$S_{w,m}$ is the effective water saturation defined as follow:

$$S_{w,m} = \frac{S_w}{1 - S_H - S_f} \quad (11)$$

Figure 2 shows these relative permeability curves.

**EXPERIMENTAL**

**Apparatus and procedure**

Artificial methane hydrate cores were prepared for experiments. The core length and diameter were 150 mm and 50 mm respectively. The core was packed into the rubber sleeve. The rubber sleeve thickness was 10 mm. The core holder as shown in Figure 3 was used for the dissociation experiments by depressurization. The core was maintained at constant pressure and temperature. One side of the core was depressurized at constant pressure to produce gas and water. Figure 4 shows the position of the sensor. The volumes of gas and water produced, temperatures of inside and outside of the core and pressures at the both ends of the core were measured.

**SIMULATION DETAILS**

**Grid system**

A cylindrical coordinate system was used. The hydrate core and the rubber sleeve were divided into 7 x 30 grids. Figure 5 shows the schematic grid system.

**Simulation conditions**

Initial input data were based on the measured data (Table 1). Boundary conditions such as heat transfer were set to reproduce the experimental conditions. The index of gas relative permeability $N_g$ in Eq. (9) and the index of water relative permeability $N_w$ in Eq. (10) were set as matching parameters for gas and water production.

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**Conditions**

Table 1 shows the experimental conditions. Two experiments with different production pressure were conducted.

<table>
<thead>
<tr>
<th></th>
<th>Exp. 1</th>
<th>Exp. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial pressure / MPa</td>
<td>10.5</td>
<td>10.4</td>
</tr>
<tr>
<td>Initial temperature / K</td>
<td>285.85</td>
<td>285.65</td>
</tr>
<tr>
<td>Production pressure / MPa</td>
<td>6.1</td>
<td>4.1</td>
</tr>
<tr>
<td>Porosity / %</td>
<td>40.5</td>
<td>39.6</td>
</tr>
<tr>
<td>Hydrate saturation / %</td>
<td>59.4</td>
<td>27.2</td>
</tr>
<tr>
<td>Gas saturation / %</td>
<td>11.4</td>
<td>24.6</td>
</tr>
<tr>
<td>Water saturation / %</td>
<td>29.2</td>
<td>48.2</td>
</tr>
</tbody>
</table>
RESULTS
Figure 6 and 7 show the comparison of cumulative gas and water produced in Exp. 1 respectively. The production volume of gas was overestimated and the production volume of water was underestimated in the case of Corey model. On the other hand, the production volumes of gas and water could be reproduced by the simulator using the model derived from Kozeny-Carman model when the indexes of gas and water relative permeability were set as 4 and 2. In this simulation conditions, the predictions agreed with the measured pressure and temperatures (Figure 8, 9). Figure 10 and 11 show the comparison of cumulative gas and water produced in Exp. 2 respectively. The measured data were reproduced by the simulator using the model derived from Kozeny-Carman model when the indexes of gas and water relative permeability were set as 8 and 2. Both experiments showed that considerable volume of water was produced during hydrate dissociation, especially at early stage of hydrate dissociation.

Figure 6 Comparison of cumulative gas produced. (Exp. 1)

Figure 7 Comparison of cumulative water produced. (Exp. 1)

Figure 8 Comparison of pressure. (Exp. 1)

Figure 9 Comparison of temperatures. (Exp. 1)

Figure 10 Comparison of cumulative gas produced. (Exp. 2)

Figure 11 Comparison of cumulative water produced. (Exp. 2)
DISCUSSION

Figure 12 shows the relative permeability curves used for the comparisons. Gas permeability decreased rapidly with increasing water saturation in both experiments. In the initial conditions of experiments, water occupied a large part of the effective pores and was the continuous phase. On the other hand, initial gas was the discontinuous phase. In depressurization method, gas generated by hydrate dissociation appears in all pores independently of their size, and this gas is discontinuous and immobile in L\textsubscript{w}-H region. So, at early stage of hydrate dissociation, water in effective pores is easily displaced by gas generated. After that, gas phase becomes high saturation due to the continuous supply of gas from hydrates and gets connected. It suggests that considerable volume of water may be produced during hydrate dissociation by depressurization, especially at early stage of hydrate dissociation in L\textsubscript{w}-H region.

![Figure 12 Relative permeability curves used for comparisons.](image)

CONCLUSION

Relative permeability curves during hydrate dissociation by depressurization were examined through comparison with numerical simulations and experimental data for fluid production. The experimental results showed that considerable volume of water was produced during hydrate dissociation. The simulator reproduced the large water production when we used the model that gas permeability decreased rapidly with increasing water saturation. Temperatures of inside and outside of the core and pressure at the end of the core were also reproduced by the simulator. This result suggests that the connate water can be easily displaced by hydrate-dissociated gas and move forward in the hydrate reservoir of high initial water saturation.

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