Oil & Natural Gas Technology

DOE Award No.: DE-FE0009927

Quarterly Research Performance Progress Report (April - June 2014)

Verification of capillary pressure functions and relative permeability equations for gas production

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Prepared for:
United States Department of Energy
National Energy Technology Laboratory

July 15, 2014

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Office of Fossil Energy

SUMMARY

Task 1.0 Project Management and Planning
<u>Done</u>

Task 2.0 Pore Network Generation
<u>Done</u>

Task 3.0 Algorithm for conductivity and hydrate dissociation
<u>Done</u>

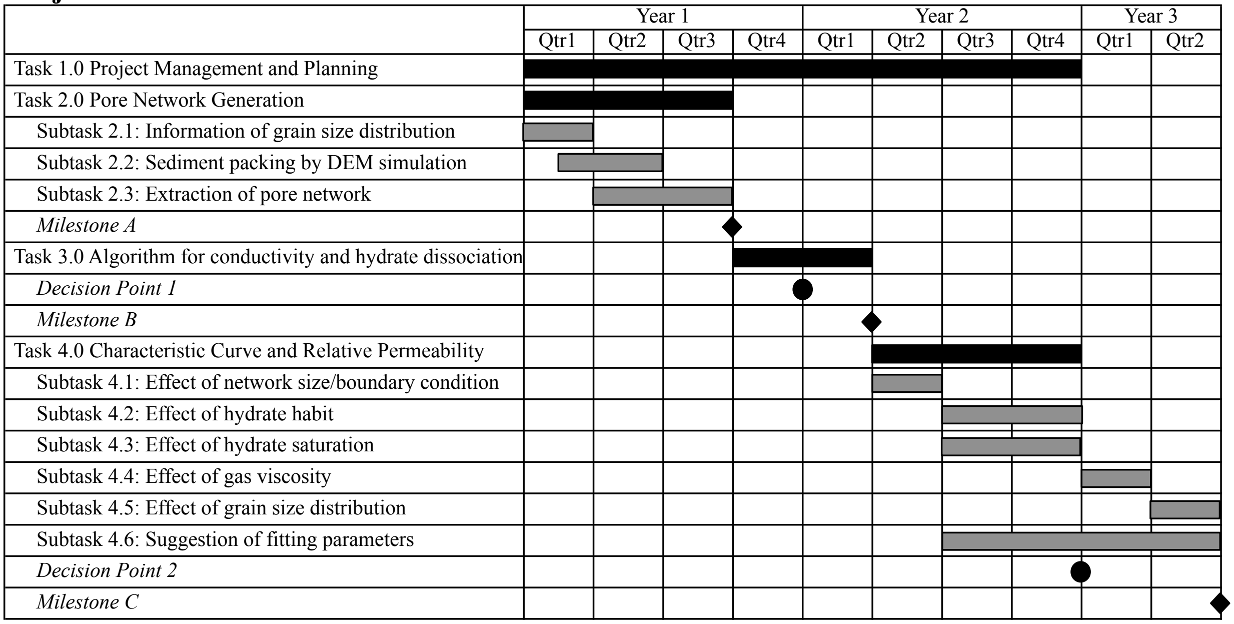
Task 4.0 Characteristic Curve and Relative Permeability
<u>In progress</u>

Subtask 4.1 Effect of network size/boundary condition
<u>Done</u>

Subtask 4.2 Effect of hydrate habit
<u>In progress</u>

Subtask 4.3 Effect of hydrate saturation
<u>In progress</u>

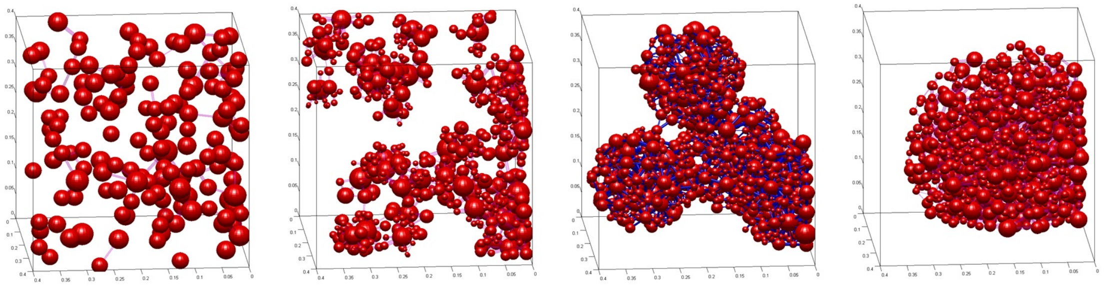
Project timeline



	Year 1				Year 2				Year 3	
	Qtr1	Qtr2	Qtr3	Qtr4	Qtr1	Qtr2	Qtr3	Qtr4	Qtr1	Qtr2
Task 1.0 Project Management and Planning	■	■	■	■	■	■	■	■		
Task 2.0 Pore Network Generation	■	■	■							
Subtask 2.1: Information of grain size distribution	▨									
Subtask 2.2: Sediment packing by DEM simulation	▨	▨								
Subtask 2.3: Extraction of pore network		▨	▨							
Milestone A			◆							
Task 3.0 Algorithm for conductivity and hydrate dissociation				■	■					
Decision Point 1				●						
Milestone B					◆					
Task 4.0 Characteristic Curve and Relative Permeability						■	■	■		
Subtask 4.1: Effect of network size/boundary condition						▨				
Subtask 4.2: Effect of hydrate habit							▨	▨		
Subtask 4.3: Effect of hydrate saturation							▨	▨		
Subtask 4.4: Effect of gas viscosity									▨	
Subtask 4.5: Effect of grain size distribution										▨
Subtask 4.6: Suggestion of fitting parameters							▨	▨	▨	▨
Decision Point 2								●		
Milestone C										◆

Summary of work during this quarter – Effect of hydrate habit

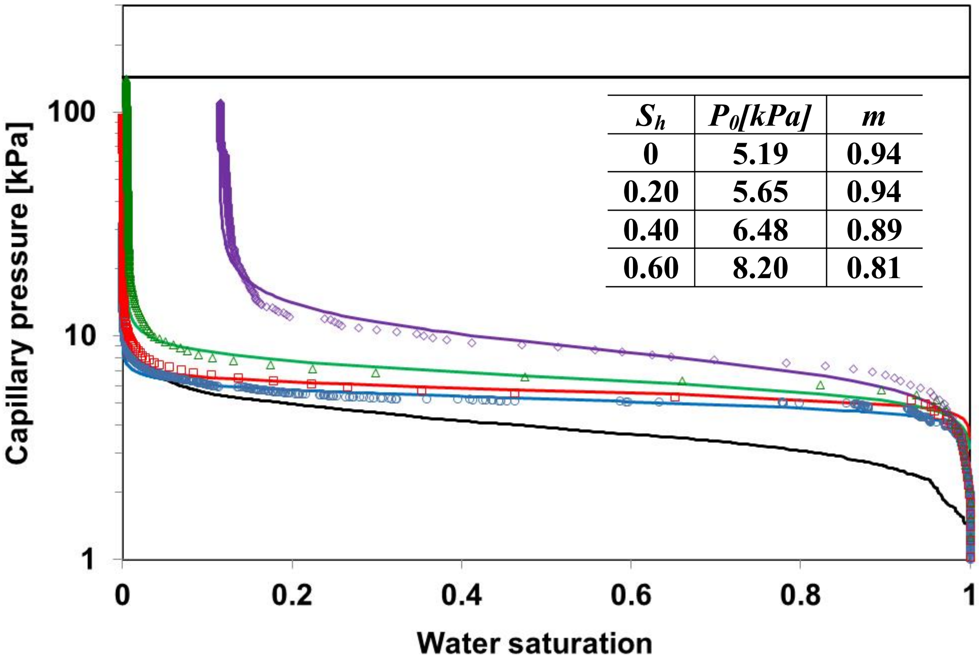
The hydrate morphology (distributed-vs.-patchy formation) affects physical properties of hydrate-bearing sediments such as electrical, hydraulic, and thermal conductivity and bulk modulus [Dai et al., 2012]. Hydrates are assigned in pores to satisfy a target initial hydrate saturation. To emulate Oswald ripening effect, pores are fully filled with either hydrate or water [Dai et al., 2012; Dai and Santamarina, 2013]. Two following assumptions are used for relative permeability and soil-water characteristic curve (SWCC) calculation to study the effect of hydrate habit on the behavior of hydrate-bearing sediments (1) hydrates fills distributed random pores (2) hydrate forms patches, whereby hydrates injects into the random pores and grows into neighboring pores which forms patches with 16,256 and 1,024 pores (Figure 1).



Largest Pores Patchy-16 Patchy-256 Patchy-1024

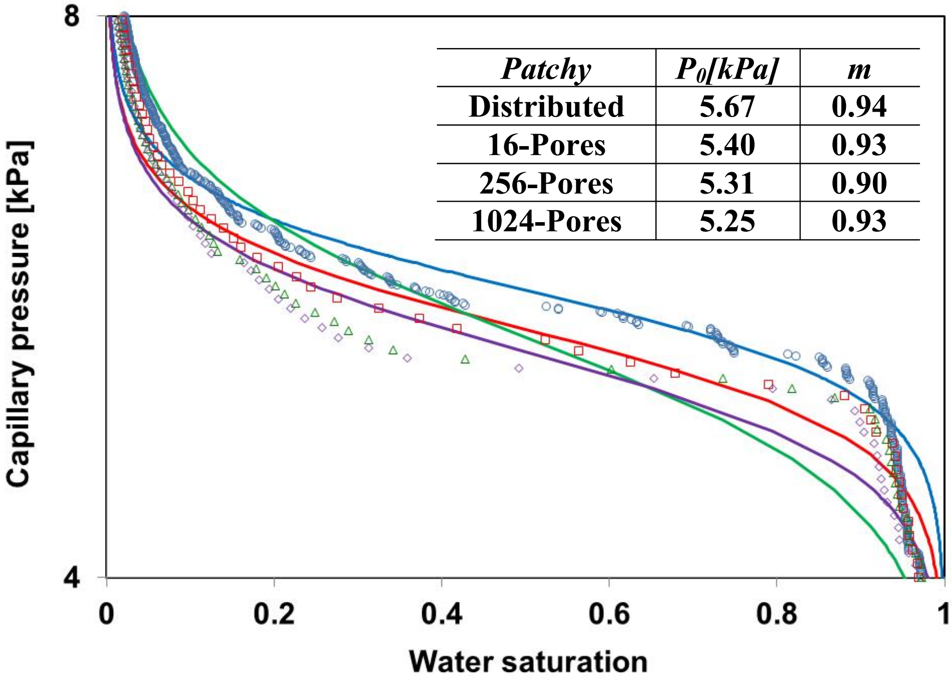
Figure 1. Different size of patches (a) distributed initial hydrate filling. (b) Patch of 16 pores (c) Patch of 256 pores. (d) Patch of 1,024 pores.

Soil water characteristic curves for S_h=0, S_h=0.2, S_h=0.4 and S_h=0.6 is shown in Figure 2. In these cases, hydrate fills distributed random pores. Calculated characteristic curves shift to higher capillary pressure as hydrate saturation increases. Characteristic curves are fitted by van-Genuchten equation and fitting parameter m-value and gas entry pressure P_0. The gas entry pressure increases and m-value decreases with hydrate saturation. Figure 3 shows characteristic curves for S_h=0.2 when hydrates forms patches of 16, 256 and 1,024 pores. As the size of patch decreases, the gas entry pressure increases. Computed fitting parameters shows that P_0 decreases with increasing the patch size, but m-value remains relatively constant.



S_h	P_0[kPa]	m
0	5.19	0.94
0.20	5.65	0.94
0.40	6.48	0.89
0.60	8.20	0.81

Figure 2. Soil-water characteristic curves for different hydrate saturations S_h. Numerical results are fitted by using van-Genuchten model, where P_0 is the air entry pressure and the m is the van-Genuchten parameter.



Patchy	P_0[kPa]	m
Distributed	5.67	0.94
16-Pores	5.40	0.93
256-Pores	5.31	0.90
1024-Pores	5.25	0.93

Figure 3. The effect of hydrate morphology on soil-water characteristic curves. Hydrate forms in patches of different number of pores (e.g., 1, 16, 256, and 1024). Numerical results are fitted by using van-Genuchten model.

Relative gas and water permeability for S_h=0.2, S_h=0.4 and S_h=0.6 with distributed hydrate filling is shown in Figure 4. As water drains as a result of gas expansion, relative water permeability decreases (Figure 4a). The simulation results for the lower initial hydrate saturation show higher relative water permeability at a given water saturation. The relative gas permeability is also dependent on the initial hydrate saturation (Figure 4b). However, the lower initial hydrate saturation, the lower relative gas permeability at a given gas saturation. Calculated fitting parameters show that m-value decreases with increasing initial hydrate saturation.

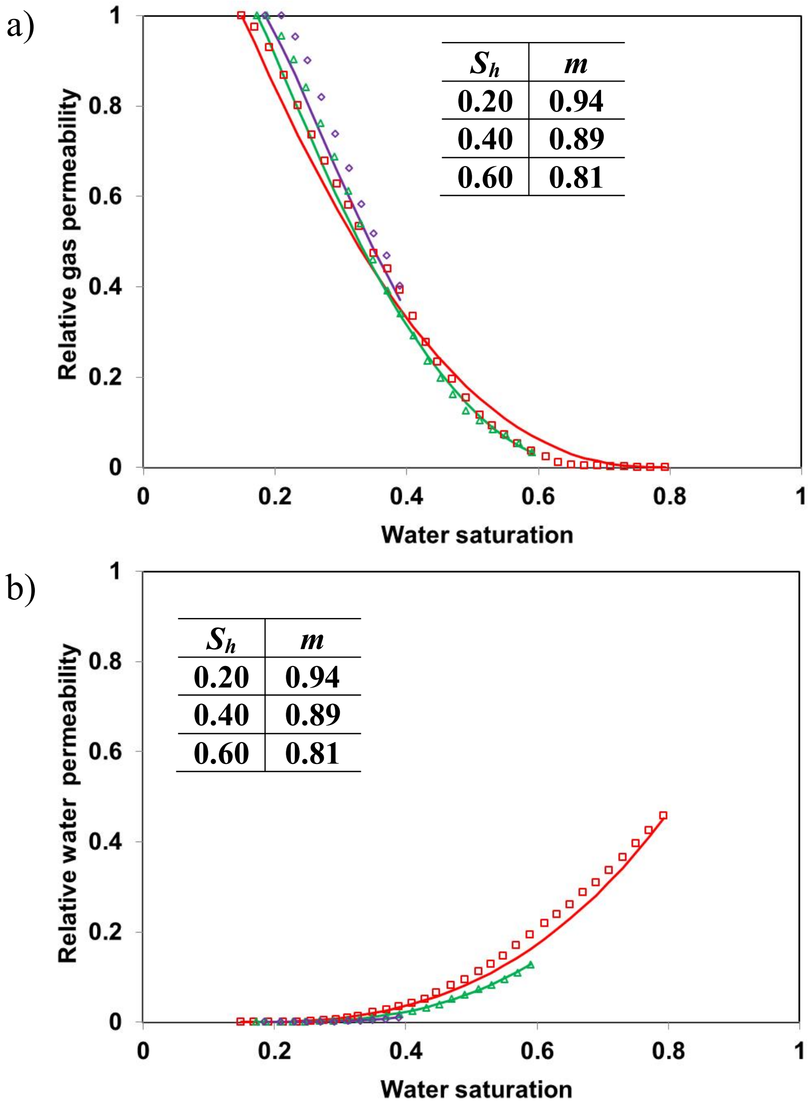
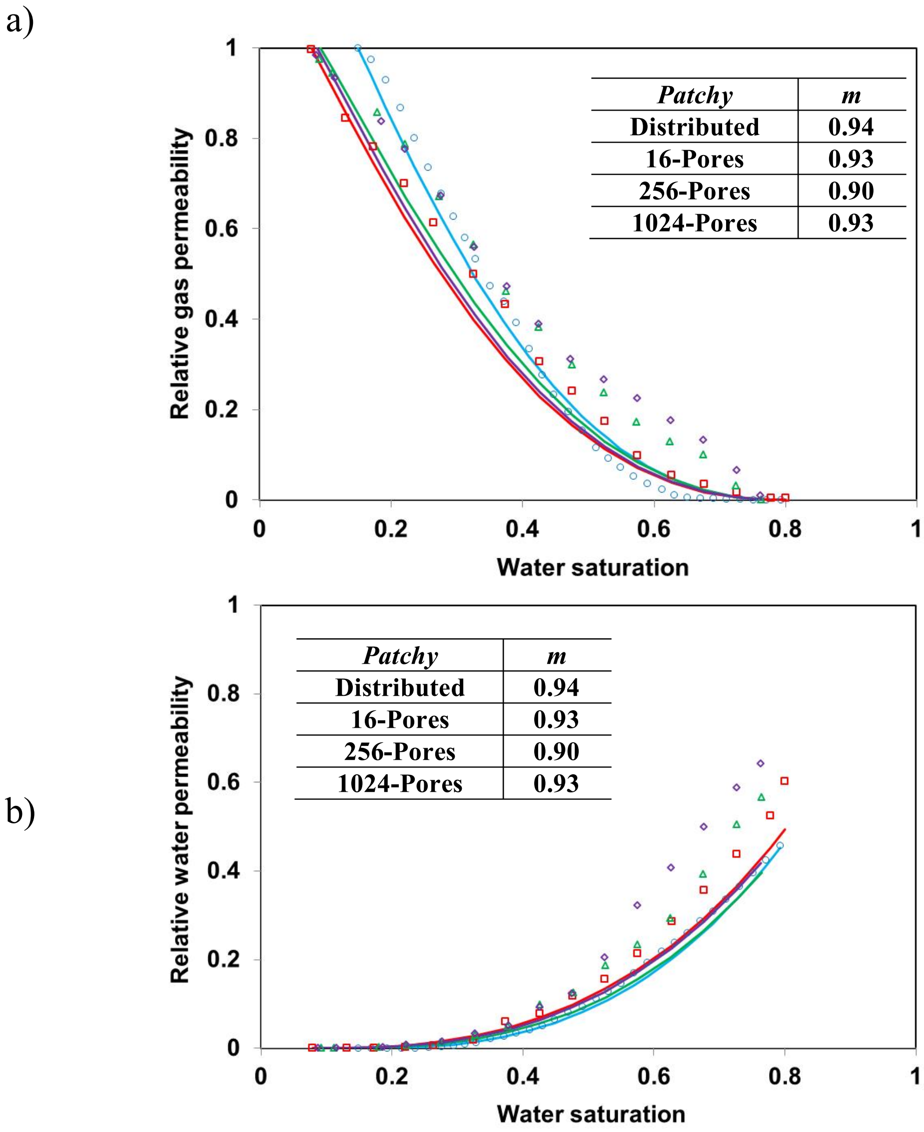


Figure 4. Relative water and gas permeability simulation results and fitted curves for different hydrate saturations (a) Relative water permeability. (b) Relative gas permeability

Gas percolation occurs at $S_g \approx 0.25$ for $S_h=0$. For the case of higher initial hydrate saturation such as $S_h=0.4$ or 0.6, gas permeability is already developed as soon as hydrates dissociate. The residual water saturation with hydrate saturation and ranges from $S_{rw}=0.15$ for $S_h=0.2$ to $S_{rw}=0.20$ for $S_h=0.6$, which is the saturation of isolated water that does not have a drainage path. Figure 5a shows the comparison for different sizes of patches for relative gas permeability. Relative gas permeability decreases with increasing the size of patches when $S_w<0.32$. There is no typical correlation between relative gas permeability and water saturation at $S_w>0.32$. However, The relative water permeability increases with size of patches (Figure 5b).



Patchy	*m*
Distributed	0.94
16-Pores	0.93
256-Pores	0.90
1024-Pores	0.93

Patchy	*m*
Distributed	0.94
16-Pores	0.93
256-Pores	0.90
1024-Pores	0.93

Figure 5. Relative water and gas permeability simulation results and fitted curves for different hydrate morphologies (a) Relative water permeability. (b) Relative gas permeability

Publication

The part of previously reported studies is published in the peer-reviewed journal as shown below. And another manuscript is being prepared.

AGU PUBLICATIONS

Geochemistry, Geophysics, Geosystems

RESEARCH ARTICLE

10.1002/2014GC005331

Relative water and gas permeability for gas production from hydrate-bearing sediments

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Key Points:

- Fitting parameters for Stone equation are suggested for gas production
- Stone equation can be used with appropriately chosen parameters
- Fitting parameters for gas permeability depend on hydrate saturation

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Citation:
Mahabadi, N., and J. Jang (2014), Relative water and gas permeability for gas production from hydrate-bearing sediments, *Geochem. Geophys. Geosyst.*, *15*, doi:10.1002/2014GC005331.

Received 7 MAR 2014
Accepted 10 MAY 2014
Accepted article online 16 MAY 2014

Abstract Relative water and gas permeability equations are important for estimating gas and water production from hydrate-bearing sediments. However, experimental or numerical study to determine fitting parameters of those equations is not available in the literature. In this study, a pore-network model is developed to simulate gas expansion and calculate relative water and gas permeability. Based on the simulation results, fitting parameters for modified Stone equation are suggested for a distributed hydrate system where initial hydrate saturations range from $S_h = 0.1$ to 0.6. The suggested fitting parameter for relative water permeability is $n_w \approx 2.4$ regardless of initial hydrate saturation while the suggested fitting parameter for relative gas permeability is increased from $n_g = 1.8$ for $S_h = 0.1$ to $n_g = 3.5$ for $S_h = 0.6$. Results are relevant to other systems that experience gas exsolution such as pockmark formation due to sea level change, CO_2 gas formation during geological CO_2 sequestration, and gas bubble accumulation near the downstream of dams.

1. Introduction

Numerical simulation studies predict the long-term behavior of hydrate-bearing sediments during gas production [*Kurihara et al.*, 2008; *Moridis et al.*, 2009; *Moridis and Reagan*, 2007a, 2007b; *Anderson et al.*, 2011; *Myshakin et al.*, 2011, 2012]. Numerical simulators for gas hydrate studies adopt many equations for coupled-process analyses. A relative permeability equation among many others embedded in numerical simulators is one of important equations because it affects gas and water production rate and gas recovery efficiency, therefore it decides the economic development of hydrate-bearing sediments [*Johnson et al.*, 2011; *Minagawa et al.*, 2004, 2007; *Kleinberg et al.*, 2003; *Gupta*, 2007; *Jang and Santamarina*, 2011, 2014; *Santamarina and Jang*, 2009, 2010]. Expression for relative water k_{rw} and gas permeability k_{rg} as a function of water saturation S_w requires fitting parameters [*Corey*, 1954; *Brooks and Corey*, 1964; *Stone*, 1970; *Anderson et al.*, 2011; *Moridis et al.*, 2008]. Therefore, the selection of proper fitting parameters for a relative permeability equation is critically important to precisely predict gas and water production rate. However, laboratory experiment or numerical simulation results are not available so far to guide the selection of adequate fitting parameters.

In this study, a pore-network model is developed to simulate hydrate dissociation and gas expansion in a distributed hydrate system where initial hydrate saturation varies from $S_h = 10\%$ to 60%. Based on the numerical simulation results of relative water and gas permeability, fitting parameters for modified Stone equation are suggested.

2. Relative Permeability Equations for Gas Hydrate Production

The relative permeability (unitless) of water k_{rw} (or gas k_{rg}) is the water (or gas) permeability (m/s) at a given water saturation S_w normalized by a reference permeability which is the water (or gas) permeability at 100% water (or gas) saturation. The permeability at the residual phase saturation may be used as a reference permeability [*Jaiswal*, 2004]. In this study, water permeability at 100% water saturation and gas permeability at residual water saturation S_{rw} (at which there is no more water displacement) are used as reference permeabilities.

Modified Stone equation shown below is frequently used for gas hydrate simulation study.

$$k_{rw} = \left(\frac{S_w - S_{rw}}{1 - S_{rw}}\right)^{n_w} \tag{1}$$

modified Stone

$$k_{rg} = \left(\frac{S_g - S_{rg}}{1 - S_{rw}}\right)^{n_g} \tag{2}$$

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