NATIONAL ENERGY TECHNOLOGY LABORATORY
OIL & GAS

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Quarterly Research Performance Progress Report

(Period Ending 6/30/2018)

Advanced Simulation and Experiments of Strongly Coupled Geomechanics and Flow for Gas Hydrate Deposits: Validation and Field Application

Project Period (10/01/2016 to 09/30/2019)

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U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY

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DISCLAIMER

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ACCOMPLISHMENTS

Objectives of the project

The objectives of the proposed research are (1) to investigate geomechanical responses induced by depressurization experimentally and numerically; (2) to enhance the current numerical simulation technology in order to simulate complex physically coupled processes by depressurization and (3) to perform in-depth numerical analyses of two selected potential production test sites: one based on the deposits observed at the Ulleung basin UBGH2-6 site; and the other based on well-characterized accumulations from the westend Prudhoe Bay. To these ends, the recipient will have the following specific objectives:

1). Information obtained from multi-scale experiments previously conducted at the recipient's research partner (the Korean Institute of Geoscience and Mineral Resources (KIGAM)) that were designed to represent the most promising known Ulleung Basin gas hydrate deposit as drilled at site UBGH2-6 will be evaluated (Task 2). These findings will be further tested by new experimental studies at Lawrence Berkeley National Laboratory (LBNL) and Texas A&M (TAMU) (Task 3) that are designed capture complex coupled physical processes between flow and geomechanics, such as sand production, capillarity, and formation of secondary hydrates. The findings of Tasks 2 and 3 will be used to further improve numerical codes.

2) Develop (in Tasks 4 through 6) an advanced coupled geomechanics and non-isothermal flow simulator ($T+M^{AM}$) to account for large deformation and strong capillarity. This new code will be validated using data from the literature, from previous work by the project team, and with the results of the proposed experimental studies. The developed simulator will be applied to both Ulleung Basin and Prudhoe Bay sites, effectively addressing complex geomechanical and petrophysical changes induced by depressurization (e.g., frost-heave, strong capillarity, cryo-suction, induced fracturing, and dynamic permeability).

Accomplished

The plan of the project timeline and tasks is shown in Table 1, and the activities and achievements during this period are listed as follows along with Table 2.

Task 1: Project management and planning

The sixth quarterly report was submitted to NETL on April 30, 2018. KIGAM has delivered the data of Subtasks 2.2 and 2.3, and thus all the in-kind cost share from KIGAM is completed and Task 2 is completed. LBNL has nearly competed Subtask 3.2 and been actively working on Subtask 3.3. Subtask 3.5 is completed. TAMU and KIGAM are continuing Subtasks 4.1 and 5.2 related to the experiment of Task 2, validation of T+M with the experimental data. Also, TAMU, KIGAM, and LBNL are actively working on Subtasks 4.3, 5.5, 5.6, and Task 6 for field-wide simulation of Ulleng Basin and PBU-106C.

The specific status of the milestones is shown in Table 2. Specific achievements including publication during this period are as follows.

Task 2: Review and evaluation of experimental data of gas hydrate at various scales for gas production of Ulleung Basin

Subtask 2.1 Evaluation of Gas hydrate depressurization experiment of 1-m scale

This task was completed previously.

Subtask 2.2 Evaluation of Gas hydrate depressurization experiment of 10-m scale

This task was completed in the previous quarter. The analysis of the data can be found in the previous quarter. The data are now being used for validation of T+M.

Subtask 2.3 Evaluation of Gas hydrate depressurization experiment of 1.5-m scale system in 3D

This task is completed. To simulate realistic phenomenon of hydrate formation in nature, water containing dissolved methane was continuously circulated through the sediment in closed flow system. Under a certain condition satisfying a hydrate equilibrium condition, hydrate starts to form in fully water-saturated condition with no gas phase, but the hydrate growth rate is very slow. At the end of 118 days of circulation, water circulation was stopped. During hydrate formation, salinity of circulating water gradually increases due to the ion exclusion effect. Hydrate saturation could be estimated by measuring concentration of chlorine ion of circulating water. In our experiment, the hydrate saturation was determined as about 25%. Fig. 2.1 shows pressure changes and estimated hydrate saturation during circulation of methane-dissolved water.

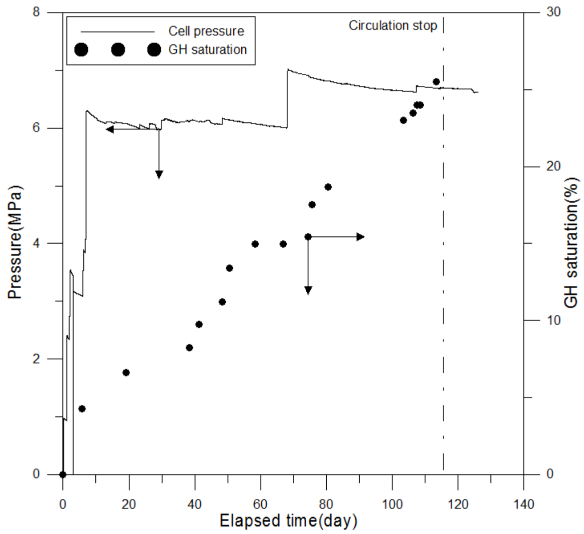

Fig. 2.1 Pressure changes and estimated hydrate saturation during circulation of methane-dissolved water

Subtask 2.4 Evaluation of gas hydrate production experiment of the centimeter-scale system

This task was completed previously.

Task 3: Laboratory Experiments for Numerical Model Verification

Subtask 3.1: Geomechanical changes from effective stress changes during dissociation

This task was completed, previously.

Subtask 3.2 Geomechanical changes from effective stress changes during dissociation – sand

The purpose of this experiment is to control hydrate formation by manipulation of pressure and temperature. A sample made from F110 sand was put in sleeve with an initial water saturation of 0.3. Shown in Fig. 3.1, thermocouples were located in the inlet an outlet, and at three positions in the confining fluid. A cooling coil constructed from Al tubing surrounding the sample near the inlet which allowed the creation of temperature gradients in the sample.

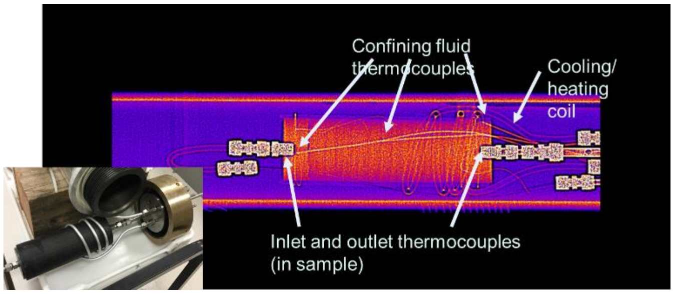

Fig. 3.1 Schematics of the experiment of Subtask 3.2

From the results in Fig. 3.2, hydrate formation in the sample was indicated by an increase in density of the sample and an uptake of 205 mL methane. Theoretical uptake of methane for the amount of water present in the sample was ~250 mL (note – do not have my lab book with me to check this number, check in the morning).

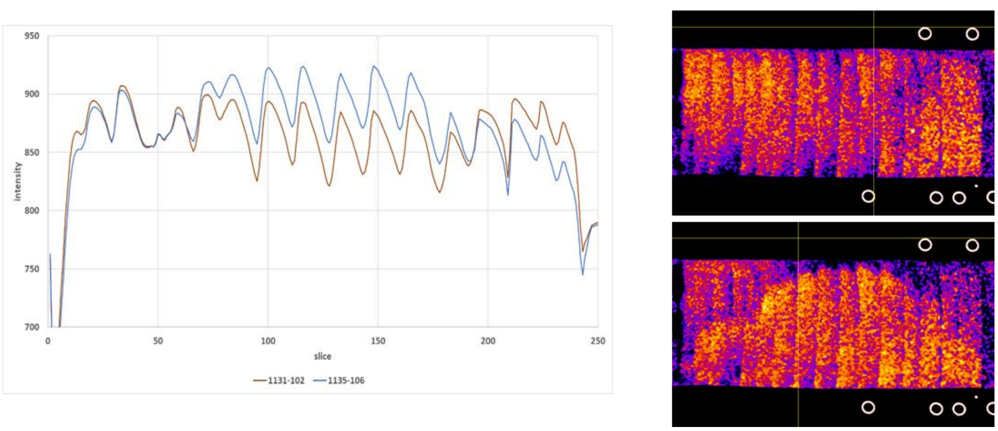

Fig. 3.2 Blue and red lines in the left figure results after and before formation, respectively. The top and bottom figures of the right side show the results before and after hydrate formation. Overall uptake of CH_4 was 205 ml.

Fig. 3.3 shows density (as pixel intensity) along the z-axis of the core. On the right are cross sections of CT scans. The yellow vertical line is added for positioning reference for the hydrate front. From, Fig. 3.4, recooling and saturation of the sample was followed by a reheating and pressure decrease from 710 psi, 680 psi, and 650 psi. Hydrate dissociated in the warming zone, reformed where temperature was at equilibrium point. An additional pressure drop to 620 psi was added to move past the hydrate wedge that was observed in the unsaturated warming.

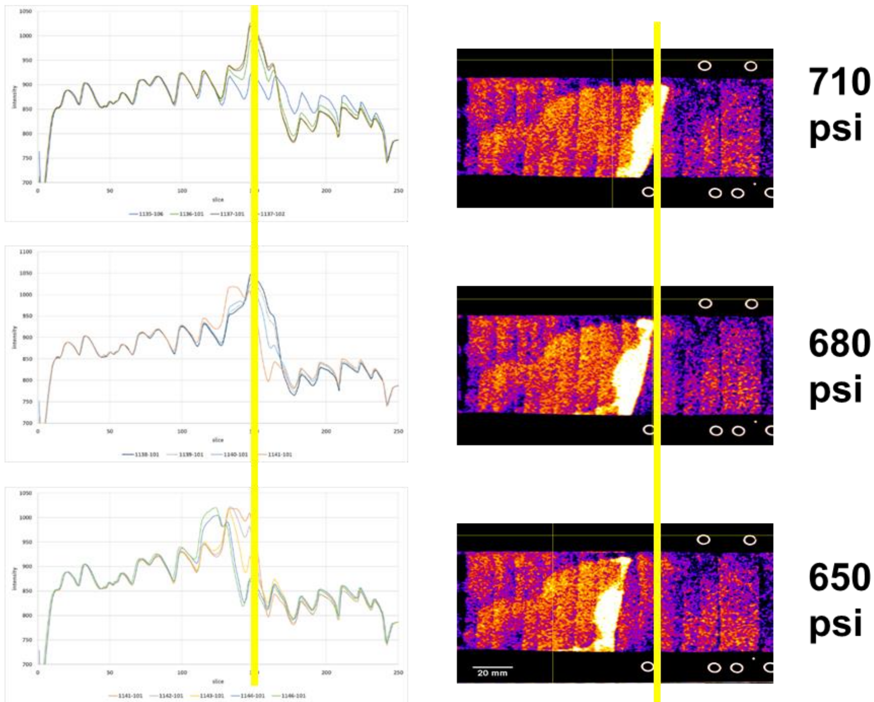

Fig. 3.3 Heating coil was set to 6.4°C, and pressure was set at 710 psi, 680 psi, and 650 psi. Hydrate dissociated in the warming zone, reformed where temperature was at equilibrium point.

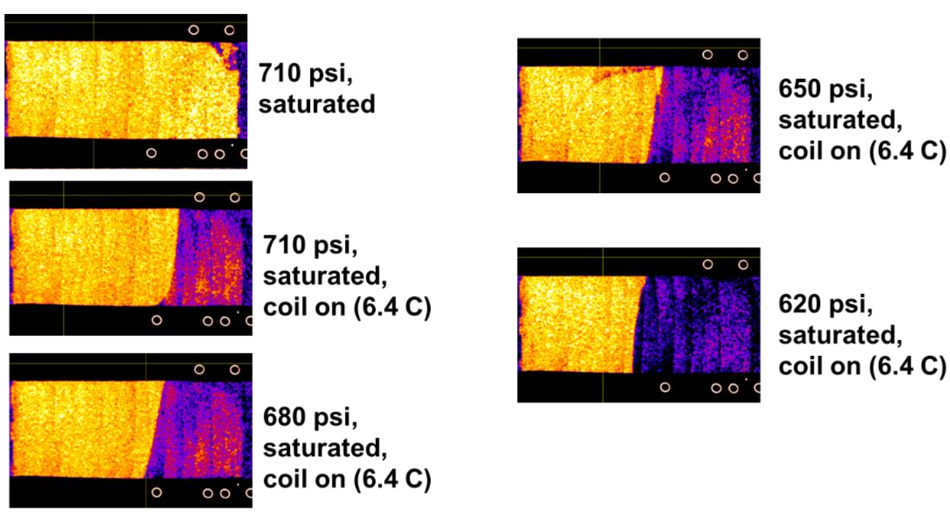

Fig. 3.4 Recooling and saturation of the sample.

Subtask 3.3 Geomechanical changes resulting from secondary hydrate and capillary pressure changes

No further progress was made in this quarter for Subtask 3.3.

Subtask 3.4 Construction of the Relative Permeability Data in Presence of Hydrate

Not initiated (future year tasks)

Subtask 3.5 Identification of Hysteresis in Hydrate Stability

This subtask is competed. Figs. 3.5 and 3.6 show the results of hysteresis of hydrate formation and dissociation. If hysteresis exists during the cycles of cooling and heating, the hydrate amount formed and the formation rate should be different for each cooling period.

From this subtask, hysteresis in hydrate formation in sand pack is shown for the first time by experimenting with a series of heating and cooling cycles at different melting temperature. Also, hysteresis cannot be measured directly in the laboratory. Hysteresis appears as a significant change in the hydrate formation time/rate during forward simulation of the cooling period for each cycle using the optimized heat-transfer and kinetics parameters. We conclude that hysteresis has added complexity due to crystallization in porous media.

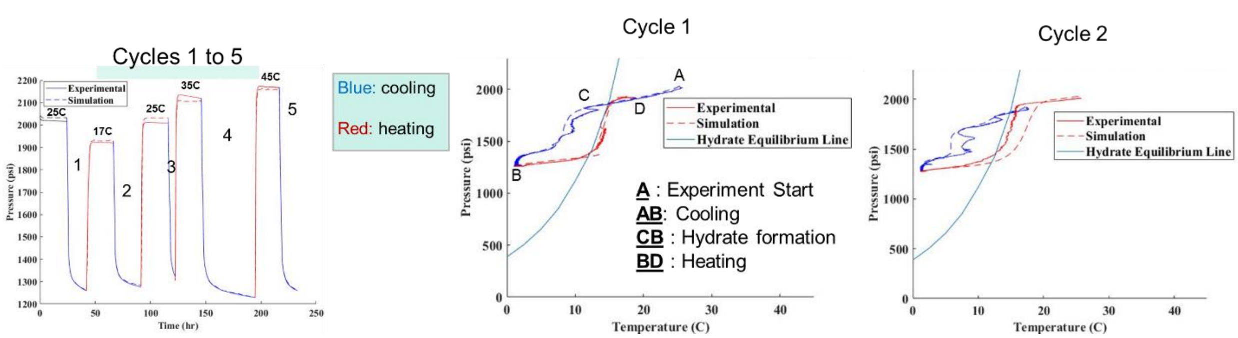

Fig. 3.5 Left: Cycles of cooling and heating. Center and Right: P-T diagrams of Cycles 1 and 2, respectively.

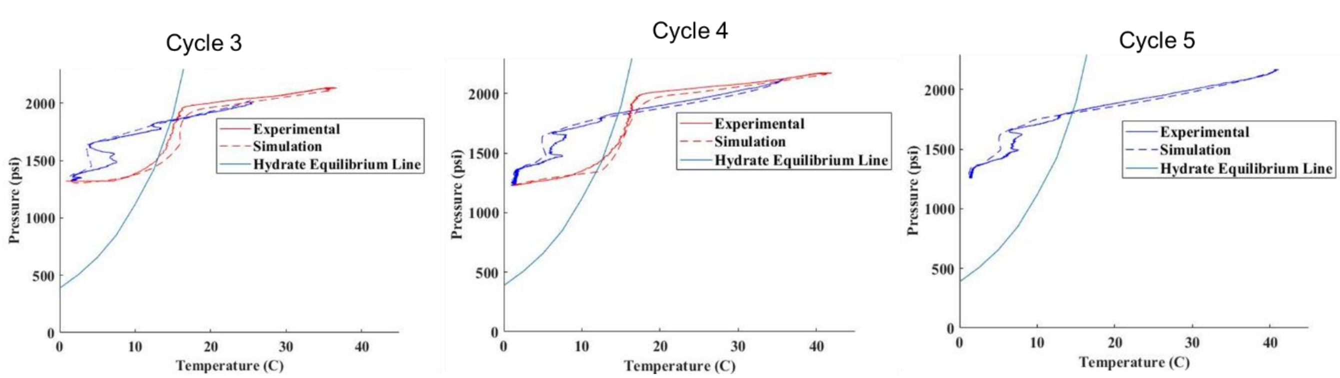

Fig. 3.6 Left, Center, Right: P-T diagrams of Cycles 3, 4 and 5, respectively.

Task 4: Incorporation of Laboratory Data into Numerical Simulation Model

Subtask 4.1 Inputs and Preliminary Scoping Calculations

Continuing the previous work, we have been post-processing the data from Subtasks 2.2 and 2.3. Displacement data are available for Subtask 2.3 while those are not available for Subtask 2.2. We are mainly focusing on extracting the measured data of pressure and displacement in Subtask 2.3, which will be used for validation with numerical simulation, Subtask 5.2.

Subtask 4.2 Determination of New Constitutive Relationships

As shown in the previous quarterly report, we have modified the subroutines of the hysteretic capillarity and relative permeability during this quarter. We will apply this advanced modeling method to numerical simulation in Tasks 5 and 6.

Also, a nonlinear model of geomechanics moduli is implemented in T+M because the model is sometimes proposed by other scientists. Specifically, the following model is available in T+M.

$$K(Ss) = K(Ss = 0\%) + (K(Ss = 100\%)\text{-}K(Ss = 0\%)) \times Ss^n,$$

where Ss is the solid phase saturation (=Sh(hydrate saturation)+SI(ice saturation)). 'K' is the drained bulk modulus. 'n' is the exponent that characterizes nonlinearity of the drained bulk modulus.

In addition, from Subtask 3.5, we propose the following constitutive relation, as well.

$$R \propto -ae^b\left(f_{eq} - f_v\right),$$

where a is a quantity related to crystallization constant times surface area of the crystallization. b is a quantity related to the activation energy. a and b in the equation include temperature-dependences but temperature is a variable computed by the simulator.

Subtask 4.3 Development of Geological Model

We have been building the geological model based on the axisymmetric domain. We first refer to the flow and geomechanical properties that were used in the previous studies of Ulleung Basin and PBU-L-106C. In previous studies, the discretized domain in geomechanics with FLAC3D might possibly cause some numerical errors near the wellbore because it did not strictly follow axisymmetric formulation. In this study, we perform simulation with strict axisymmetric formulation in the finite element code, which is being used in Subtasks 5.5 and 5.6 .

Task 5: Modeling of coupled flow and geomechanics in gas hydrate deposits

Subtask 5.1 Development of a coupled flow and geomechanics simulator for large deformation

This task was completed previously.

Subtask 5.2 Validation with experimental tests of depressurization

Continuing the previous work, we have been validating T+M, finding matching parameters of geomechanics and flow, conducted in Subtask 2.1. Fig. 5.1 shows the ongoing process of calibration and validation of T+M with the experimental results. Compared to the result in the previous quarter, we have obtained a better matched result for the case of Sh=30%. We keep matching the numerical results with the experimental data for the other cases, varying the geomechanical properties.

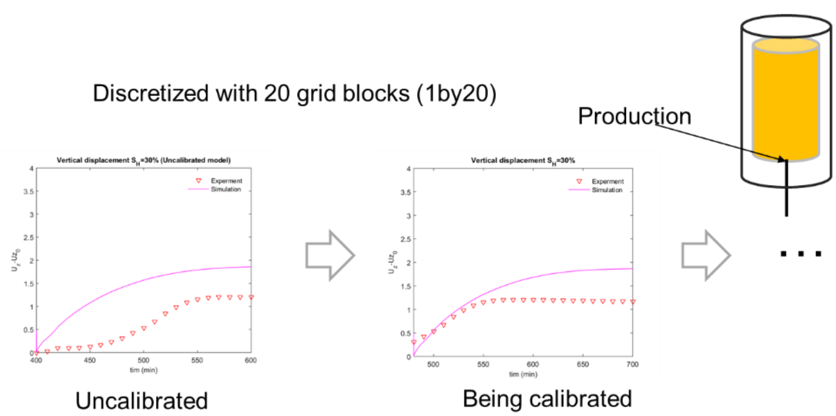

Fig. 5.1 Ongoing model calibration for validation of T+M with the experimental results of Subtask 2.1.

Subtask 5.3 Modeling of sand production and plastic behavior

We performed the preliminary study of elastoplasticity in large deformation with single phase flow. Fig. 5.2 shows the evolution of plasticity near the wellbore during production by depressurization. The failed area implies the potential well-bore collapse or sand production. We are applying this developed sub-routine to the gas hydrate simulation of large deformation.

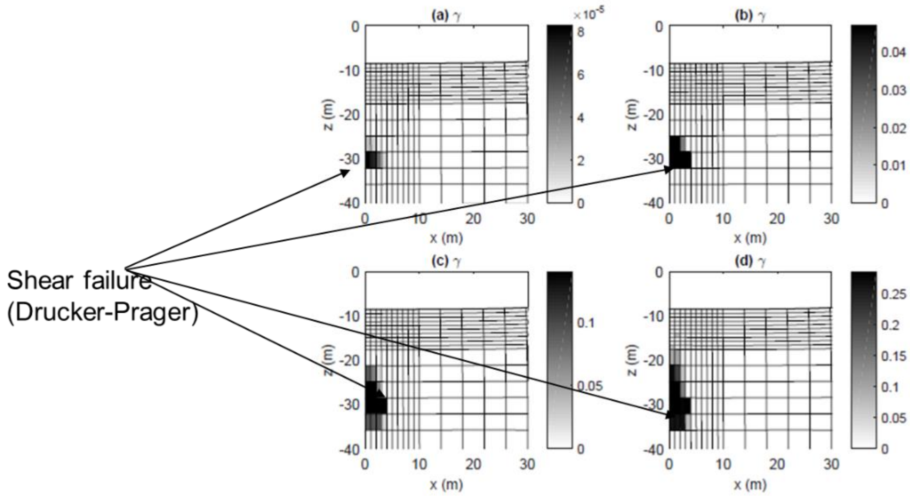

Fig. 5.2 Evolution of the failed area. The failed regions are related to well-bore collapse or sand production.

Subtask 5.4 Modeling of induced changes by formation of secondary hydrates: Frost-heave, strong capillarity, and induced fracturing

Continuing the previous work, we are currently coupling the fracturing simulator of ROCMECH with TOUGH+Hydrate. Fig. 5.3 shows the dual mesh systems for flow and geomechanics (ie., Voronoi element for flow and triangles for geomelchanics) in the coupling. This dual mesh yields orthogonal flow at an interface of the flow mesh. We have constructed the mesh generator that can provide information of data structures between the two individual meshes, such as element-node, edge-node, element-edge, and node-node. Shown in Fig. 5.4, we performed flow simulation to test the mesh generator and TOUGH+ single phase flow with the Voronoi mesh. It provides a reasonable result of pressure distribution.

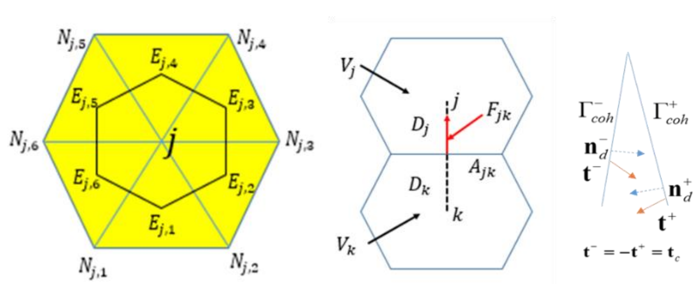

Fig. 5.3 The dual-mesh system of the fracturing T+M.

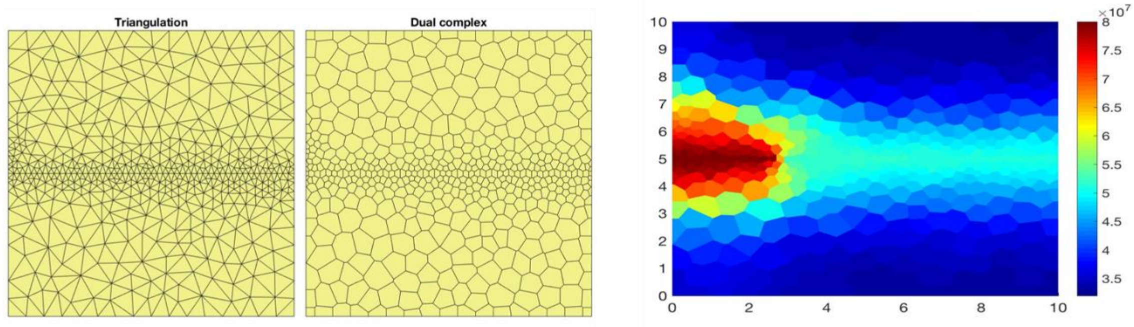

Fig. 5.4 A preliminary test of flow simulation under the dual-mesh system. Left: the dual mesh. Right: pressure distribution during production of single phase flow.

Subtasks 5.5 and 5.6 Field-scale simulation of PBU L106 and Ulleung Basin

Continuing the previous work, we are testing the field-wide simulation of two-way coupled flow and geomechanics for the UBGH2-6 site located in Ulleung Basin from the geological model made in Subtask 4.3. Fig. 5.5 shows a test results of pressure distribution during one day production, which looks good. We are investigating more on the simulation performance for various scenarios of depressurization.

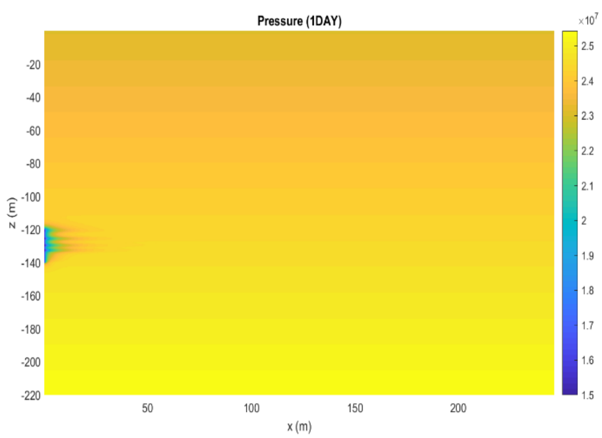

Fig. 5.5 Pressure distribution after one-day production by depressurization in UBGH2-6.

Task 6: Simulation-Based Analysis of System Behavior at the Ignik-Sikumi and Ulleung Hydrate Deposits

No further progress was made during this quarter.

PRODUCTS

Paper published during this quarter

Kim J., 2018, Unconditionally Stable Sequential Schemes for All-way Coupled Thermoporomechanics: Undrained-Adiabatic and Extended Fixed-Stress Splits, Computer Methods in Applied Mechanics and Engineering, 341:93-112. This fund is acknowledged.

Paper submitted (under review) during this quarter

Yoon H.C., Zhou P., Kim J., Hysteresis Modeling of Capillary Pressure and Relative Permeability by using the Theory of Plasticity (Originally SPE-182709-MS), submitted to Journal of Computational Physics.

Continuing the previous activity of the web-conference, all parties of TAMU, LBNL, KIGAM have been participating in the 2nd International Gas Hydrate Code Comparison Study teleconference (IGHCCS2) held every two weeks online.

BUDGETARY INFORMATION

Table 3 shows the information of the budget for this project and the expenditure up to 06/30/2018.

Table 1 – Initial project timeline and milestones (Gantt Chart)

	FY17				FY18				FY19			
Quarter	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
Task 1.0. Project Management/Planning	A											
Task 2.0. Experimental study of gas hydrate in various scales for gas production of Ulleung Basin												
Subtask 2.1. Depressurization of 1 m scale in 1D				B								
Subtask 2.2 Depressurization of 10-m scale in 1D							C					
Subtask 2.3. Depressurization of 1.5-m scale in 3D										D		
Subtask 2.4. Revisit to the centimeter-scale system												
Task 3.0. Laboratory Experiments for Numerical Model Verification												
Subtask 3.1. Effective stress changes during dissociation				E								
Subtask 3.2. Sand production								F				
Subtask 33. Secondary hydrate and capillary pressure changes												G
Subtask 3.4. Relative Permeability Data												
Subtask 3.5. Hysteresis in Hydrate Stability												

Task 4.0. Incorporation of Laboratory Data into Numerical Simulation Model												
Subtask 4.1. Inputs and Preliminary Scoping Calculations									H			
Subtask 4.2. Determination of New Constitutive Relationships												
Subtask 4.3. Development of Geological Model												
Task 5.0. Modeling of coupled flow and geomechanics in gas hydrate deposits												
Subtask 5.1 Development of a coupled flow and geomechanics simulator for large deformation				I								
Subtask 5.2 Validation with experimental tests of depressurization										J		
Subtask 5.3 Modeling of sand production and plastic behavior								K				
Subtask 5.4 Frost-heave, strong capillarity, and induced fracturing												L
Subtask 5.5 Field-scale simulation of PBU L106												
Subtask 5.6 Field-wide simulation of Ulleung Basin												
Task 6.0. Simulation-Based Analysis of System Behavior at the Ignik-Sikumi and Ulleung Hydrate Deposits												M

Table 2. Milestones Status

Milestone	Description	Planned Completion	Actual Completion	Status / Comments
Task 1 Milestones				
Milestone A	Complete the kick-off meeting and revise the PMP	12/31/17	1/14/2017	Kickoff meeting held 11/22/17, revised PMP finalized 1/17/17
Task 2 Milestones				
Milestone B	Complete analysis of 1 m-scale experiment in 1D and validation of the cm-scale system (FY17, Q4)	9/30/2017		Completed.
Milestone C	Complete analysis of 10m-scale experiment in 1D	6/30/2018		Completed.
Milestone D	Complete analysis of 1.5m-scale experiment in 3D			Completed.
Task 3 Milestones				
Milestone E	Complete geomechanical changes from effective stress changes during dissociation and construction of the relative permeability data	9/30/2017		Completed
Milestone F	Complete geomechanical changes from effective stress changes during dissociation (sand production) and hysteresis in hydrate stability	9/30/2018		
Milestone G	Complete geomechanical changes resulting from	9/30/2019		

	secondary hydrate and capillary pressure changes			
Task 4 Milestones				
Milestone H	Complete inputs and preliminary scoping calculations, determination of New Constitutive Relationships, development of Geological Model	12/31/2018		
Task 5 Milestones				
Milestone I	Complete development of a coupled flow and geomechanics simulator for large deformation, validation with experimental tests of Subtasks 2.1 and 2.4.	9/30/17		Completed.
Milestone J	Validation with experimental tests of Task 2 and 3	3/31/2019		
Milestone K	Complete modeling of sand production and plastic behavior, validation with experimental tests of Subtasks 2.2	9/30/2018		
Milestone L	Complete field-scale simulation of the Ulleung Basin and PBU L106	3/31/2019		
Task 6 Milestones				
Milestone M	Complete Task 6	9/30/2019		

Table 3 Budget information

Baselinie Reporting Quarter	**Budget Period 1**							
	Q1		Q2		Q3		Q4	
	10/01/16-12/31/16		01/01/17-03/31/17		04/01/17-06/30/17		07/01/17-09/30/17	
	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total
Baselinie Cost Plan								
Federal (TAMU)	$37,901	$37,901	$57,809	$95,711	$43,967	$139,678	$34,206	$173,884
Federal (LBNL)	$18,750	$18,750	$18,750	$37,500	$18,750	$56,250	$18,750	$75,000
Non-Federal Cost Share	$6,986	$6,986	$6,986	$13,972	$6,986	$20,958	$656,986	$677,944
Total Planned	$63,637	$63,637	$83,545	$147,183	$69,703	$216,886	$709,942	$926,828
Actual Incurred Cost								
Federal (TAMU)	$0	$0	$10,235	$10,235	$57,085	$67,321	$54,167	$121,488
Federal (LBNL)	$0	$0	$0	$0	$0	$0	$8,500	$8,500
Non-Federal Cost Share	$0	$0	$6,986	$6,986	$6,986	$13,972	$156,986	$170,958
Total incuured cost	$0	$0	$17,221	$17,221	$64,071	$81,293	$219,653	$300,946
Variance								
Federal (TAMU)	($37,901)	($37,901)	($47,574)	($85,475)	$13,118	($72,357)	$19,961	($52,396)
Federal (LBNL)	($18,750)	($18,750)	($18,750)	($37,500)	($18,750)	($56,250)	($10,250)	($66,500)
Non-Federal Cost Share	($6,986)	($6,986)	$0	($6,986)	$0	($6,986)	($500,000)	($506,986)
Total variance	($63,637)	($63,637)	($66,324)	($129,961)	($5,632)	($135,593)	($490,289)	($625,882)

Baselinie Reporting Quarter	Budget Period 2							
	Q1		Q2		Q3		Q4	
	10/01/17-12/31/17		01/01/18-03/31/18		04/01/18-06/30/18		07/01/18-09/30/18	
	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total
Baselinie Cost Plan								
Federal (TAMU)	$42,481	$42,481	$35,307	$77,788	$46,367	$124,155	$39,908	$164,063
Federal (LBNL)	$18,750	$18,750	$18,750	$37,500	$18,750	$56,250	$18,750	$75,000
Non-Federal Cost Share	$6,986	$6,986	$6,986	$13,972	$6,986	$20,958	$6,986	$27,944
Total Planned	$68,217	$68,217	$61,043	$129,260	$72,103	$201,363	$65,644	$267,007
Actual Incurred Cost								
Federal (TAMU)	$35,832	$35,832	$31,662	$67,494	$35,510	$103,004		
Federal (LBNL)	$45,952	$45,952	$18,130	$64,082	$0	$64,082		
Non-Federal Cost Share	$6,986	$6,986	$6,986	$13,972	$506,986	$520,958		
Total incuured cost	$88,770	$88,770	$56,778	$145,548	$542,496	$688,044		
Variance								
Federal (TAMU)	($6,650)	($6,650)	($3,645)	($10,294)	($10,857)	($21,151)		
Federal (LBNL)	$27,202	$27,202	($620)	$26,582	($18,750)	$7,832		
Non-Federal Cost Share	$0	$0	$0	$0	$500,000	$500,000		
Total variance	$20,552	$20,552	($4,265)	$16,288	$470,393	$486,681		

Baselinie Reporting Quarter	Budget Period 3							
	Q1		Q2		Q3		Q4	
	10/01/18-12/31/18		01/01/19-03/31/19		04/01/19-06/30/19		07/01/19-09/30/19	
	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total
Baselinie Cost Plan								
Federal (TAMU)	$43,543	$43,543	$36,189	$79,733	$47,526	$127,259	$41,209	$168,468
Federal (LBNL)	$18,750	$18,750	$18,750	$37,500	$18,750	$56,250	$18,750	$75,000
Non-Federal Cost Share	$6,986	$6,986	$6,986	$13,972	$6,986	$20,958	$6,986	$27,944
Total Planned	$69,279	$69,279	$61,925	$131,205	$73,262	$204,467	$66,945	$271,412
Actual Incurred Cost								
Federal (TAMU)								
Federal (LBNL)								
Non-Federal Cost Share								
Total incuured cost								
Variance								
Federal (TAMU)								
Federal (LBNL)								
Non-Federal Cost Share								
Total variance								

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