Oil & Natural Gas Technology

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Quarterly Research Performance Progress Report (Period ending 12/31/2013)

THCM Coupled Model For Hydrate-Bearing Sediments: Data Analysis and Design of New Field Experiments (Marine and Permafrost Settings)

Project Period (10/1/2013 to 09/30/2015)

Submitted by:

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NETL

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DISCLAIMER

ACCOMPLISHMENTS

The experimental study of hydrate bearing sediments has been hindered by the very low solubility of methane in water (lab testing), and inherent sampling difficulties associated with depressurization and thermal changes during core extraction. This situation has prompted more decisive developments in numerical modeling in order to advance the current understanding of hydrate bearing sediments, and to investigate/optimize production strategies and implications. The goals of this research is to addresses the complex thermo-hydro-chemo-mechanical THCM coupled phenomena in hydrate-bearing sediments, using a truly coupled numerical model that incorporates sound and proven constitutive relations, satisfies fundamental conservation principles. This tool will allow us to better analyze available data and to further enhance our understanding of hydrate bearing sediments in view of future field experiments and the development of production technology.

ACCOMPLISHED

The main accomplishments for this first period address Tasks 1, 2 and 3 of the original research plan, and include:

- completion of project management plan (PMP) (Task 1)
- selection of the PhD Students that will form the project team during the first year.
- preliminary training
- early studies

Training

The two PhD students contemplated for the first year joined the project during the first month (October 2013). Besides their course work, they have been fully dedicated to advancing their understanding of hydrates behavior, hydrate dissociation, natural sediments, numerical and analytical methods in hydrates research. As for the TAMU Ph.D.student (Mr. Xuerui (Gary) Gai) his trained included the graduate course CVEN 673 “Transport Phenomena in Porous Media”. This class covers the fundamentals of THCM behavior of sediments and rocks. It is also a good introduction to CODE-BRIGHT, the numerical tool to be used in this project. As for the GT Ph.D. student (Mr. Z Sun) he has continued with his formation on advance analytical methods and HBS behavior.

Early studies

The preliminary studies include (Task 2 and 3)

- Literature review (Task 2a – ongoing), including.
    - Published constitutive models for hydrates bearing sediments (HBS)
    - Specific Energy and Thermal Transport values in coupled THCM process involving gas hydrate sediments (Table 1).
    - Phase boundaries for water-gas mixtures in the pressure-temperature space (Figure 1).
    - Analytical and numerical modeling of HBS
- Hydrate-bearing marine sediments (Task 2b – ongoing), including
    - Upgrade of constitutive models for HBS.

- Hydrate-bearing sediments in the permafrost (Task 2c – ongoing), including
    - Improving the current understanding and modeling of the effect of subzero temperatures and cryogenic suction on sediments behavior.
- Validation of implemented functions (Task 3a – ongoing), including
    - Constitutive equations have been implemented in CODE_BIRGTH and compared against analytical values (from Task 2). Table 2 presents the list of implemented constitutive equations and equilibrium restrictions.
- Synthetic numerical tests (Task 3b – ongoing), including
    - The synthetic numerical tests have been defined and the corresponding simulations have been started. Figure 2 presents the suggested loading paths in the P-T plane.
- Code comparison analyses (Task 3c – ongoing), including
    - We have started with the simulations aimed at comparing our code against other ones developed to model the behavior of HBS. We are using the benchmark exercises prepared in the context of "The National Methane Hydrates R&D Program: Methane Hydrate Reservoir Simulator Code Comparison Study" (http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/MH_CodeCompare/MH_CodeCompare.html
    - We are working on Benchmark Test # 1 (see Figures 3 to 5). More details are provided below.

Plan - Next reporting period

We will advance analytical and numerical fronts to enhance our code to solve coupled THCM problems involving with HBS, with renewed emphasis on simulating the natural processes under in-situ conditions and gas production.

Milestones for each budget period of the project are tabulated next. These milestones are selected to show progression towards project goals.

	Milestone Title Planned Date and Verification Method	Actual Completion Date	Comments
Title Related Task / Subtasks Planned Date Verification method	Complete literature review 2.0 / 2.a March 2014 Report	March 2014	Progressing as planned
Title Related Task / Subtasks Planned Date Verification method	Complete updated Constitutive Equations 2.0 / 2.b & 2.c June 2014 Report (with preliminary validation data)	June 2014	Progressing as planned
Title Related Task / Subtasks Planned Date Verification method	Validate new THCM constitutive equations 3.0 / 3.a, 3.b & 3.c September 2014 Report (with first comparisons between experimental and numerical results)	September 2014	Progressing as planned
Title Related Task / Subtasks Planned Date Verification method	Complete close-form analytical solutions 4.0 / 4.a & 4.b February 2015 Report (with analytical data)	February 2015	Activities not started yet
Title Related Task / Subtasks Planned Date Verification method	Complete numerical analyses 5.0 / 5.a, 5.b & 5.c July 2015 Report (with analytical and numerical data)	July 2015	Activities not started yet
Title Related Task / Subtasks Planned Date Verification method	Complete THCM-Hydrate code modifications 6.0 / 6.a June 2015 Report (with numerical data)	June 2015	Activities not started yet
Title Related Task / Subtasks Planned Date Verification method	Complete production optimization 7.0 / 7.a, 7.b, 7.c, 7.d & 7.e September 2015 Report (with numerical data)	September 2015	Activities not started yet

Table 1: Specific Energy and Thermal Transport – Selected Representative Values

Species and Phases	Specific Energy		Transport
	Expression	specific heat - latent heat	thermal conduct.
water - vapour	$e_g^w = L_{evap} + c_{wv}\left(T - T_o\right)$	L_{evap}= 2257 J.g^{-1} c_{wv} = 2.1 J.g^{-1}K^{-1}	0.01 W m^{-1}K^{-1}
water - liquid	$e_w = c_{wl}\left(T - T_o\right)$	c_{wl} = 4.2 J.g^{-1}K^{-1}	0.58 W m^{-1}K^{-1}
water – ice	$e_{ice} = L_{fuse} + c_{wice}\left(T - T_o\right)$	L_{fuse} = 334 J.g^{-1} c_{wice} = 2.1 J.g^{-1}K^{-1}	2.1 W m^{-1}K^{-1}
methane gas	$e_m = c_m\left(T - T_o\right)$	c_m= 1.9 J.g^{-1}K^{-1} V=const c_m= 2.5 J.g^{-1}K^{-1} P=const	0.01 W m^{-1}K^{-1}
hydrate (1)	$e_h = L_{diss} + c_h\left(T - T_o\right)$	L_{diss}= 339 J.g^{-1} c_h= 2.1 J.g^{-1}K^{-1}	0.5 W m^{-1}K^{-1}
mineral	$e_s = c_s\left(T - T_o\right)$	c_s= 0.7 J.g^{-1}K^{-}1 quartz c_s= 0.8 J.g^{-1}K^{-1} calcite	8 W m^{-1}K^{-1} quartz 3 W m^{-1}K^{-1} calcite

Source: CRC handbook and other general databases. (1) Waite, http://woodshole.er.usgs.gov/operations/hi_fi/index.html; Handa 1986.

Note: the sign of the latent heat is adopted to capture endothermic-exothermic effects during phase transformation.

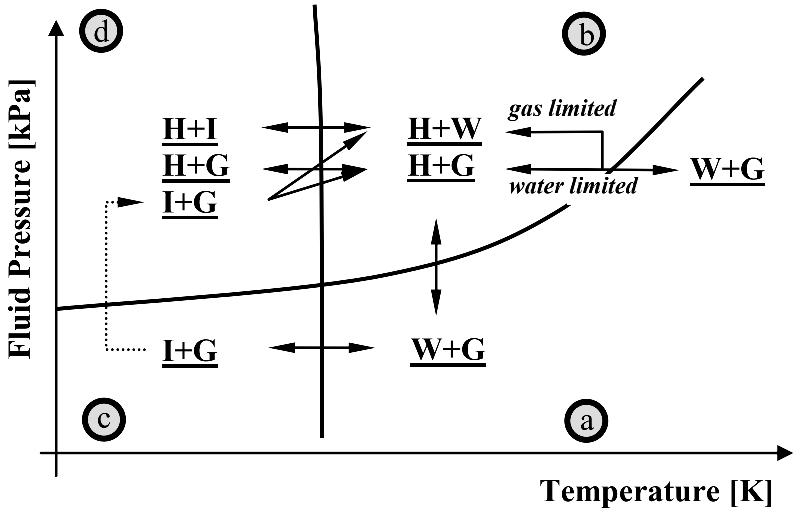
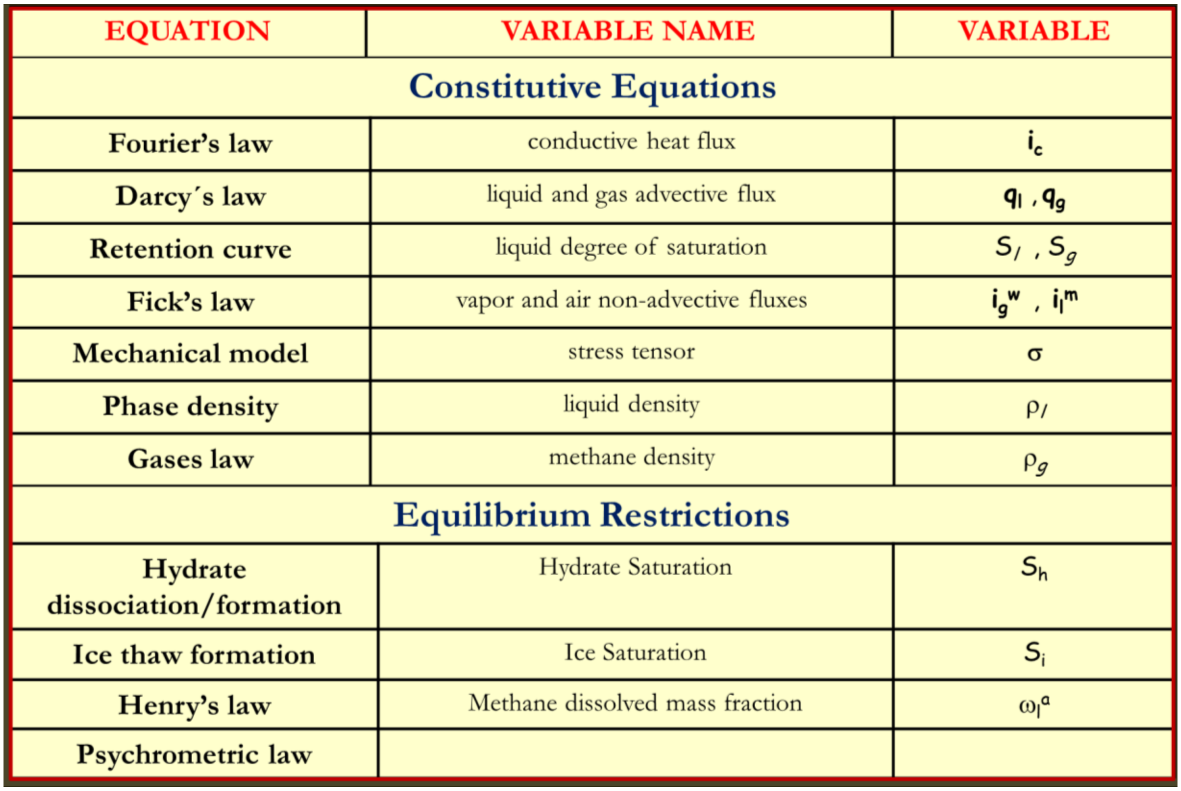


Figure 1: Phase boundaries for water-gas mixtures in the pressure-temperature space. The phases in each quadrant depend on the availability of water and gas, and the PT trajectory.

Table 2: Constitutive equations and equilibrium restrictions implemented to model the behavior of HBS



EQUATION	VARIABLE NAME	VARIABLE
Constitutive Equations		
Fourier's law	conductive heat flux	$\mathbf{i}_c$
Darcy´s law	liquid and gas advective flux	$\mathbf{q}_l$, $\mathbf{q}_g$
Retention curve	liquid degree of saturation	S_l , S_g
Fick's law	vapor and air non-advective fluxes	$\mathbf{i}_g^w$, $\mathbf{i}_l^m$
Mechanical model	stress tensor	σ
Phase density	liquid density	ρ_l
Gases law	methane density	ρ_g
Equilibrium Restrictions		
Hydrate dissociation/formation	Hydrate Saturation	S_h
Ice thaw formation	Ice Saturation	S_i
Henry's law	Methane dissolved mass fraction	ω_l^a
Psychrometric law		

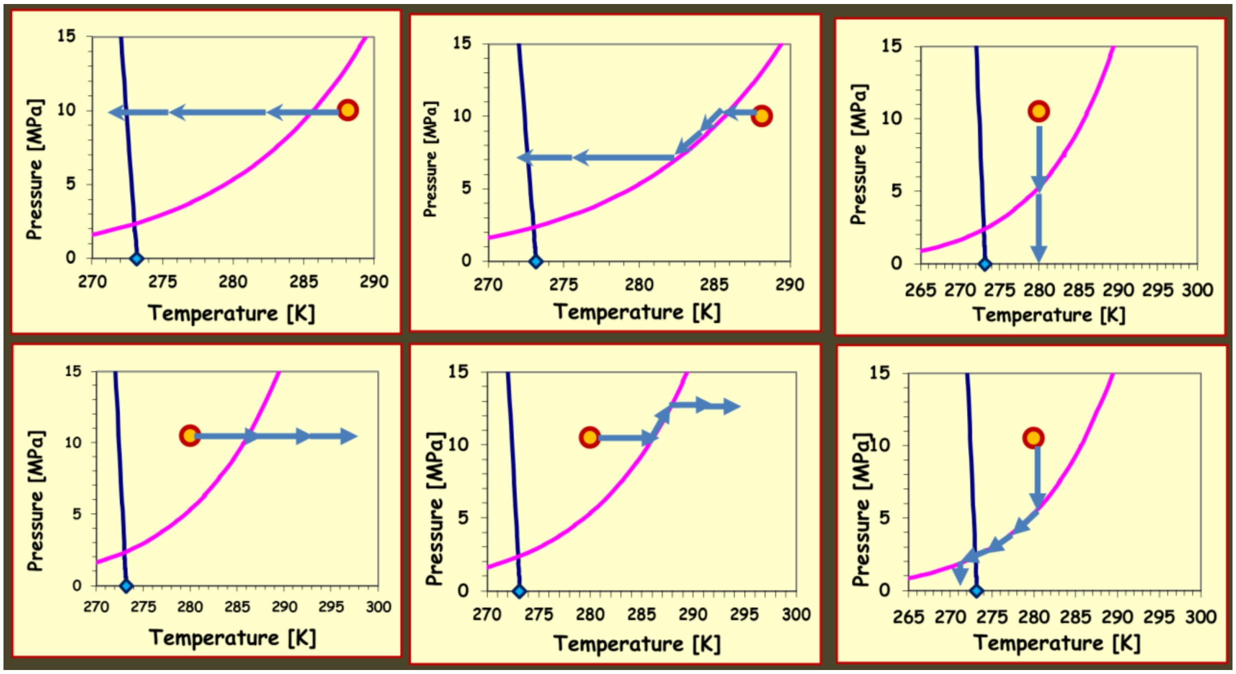


Figure 2: Some of the loading paths in the P-T plane suggested for the synthetic numerical tests.

Benchmark Test 1

We have started with the validation of our code using the benchmarks prepared in the context of “The National Methane Hydrates R&D Program: Methane Hydrate Reservoir Simulator Code Comparison Study” (http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/MH_CodeCompare/MH_CodeCompare.html

Benchmark Test # 1 is related to the analysis of “Non-isothermal Multifluid Transition to Equilibrium”. We are copying below the description of Benchmark Test # 1.

Processes of interest to the simulation of CH4 production from gas hydrates in porous media include multifluid flow and heat transport along with complex phase transitions, including hydrate dissociation and formation. Before executing problems with the additional complexities involved with the gas hydrate phase, a base case problem has been designed to examine the numerical simulation of multifluid flow and heat transport processes with a single phase transition from aqueous saturated to unsaturated conditions for a water-CH4 system outside the stability region for gas hydrate formation. The problem involves a horizontal one-dimensional closed domain (no flow boundary conditions), initialized with gradients in aqueous pressure, gas pressure, and temperature that yield aqueous saturated conditions on half of the domain and aqueous unsaturated conditions on the other half of the domain. The simulation then proceeds to an equilibrium condition in pressure and temperature. The results of numerical simulations of CH4 hydrate formations in geologic media largely depend on the computation of thermodynamic and transport properties. Therefore, a portion of this problem involves reporting property data for selected temperatures and pressures.

After execution and comparison of simulator results for this base case problem, a companion problem will be defined that includes a methane hydrate phase and associated phase transitions as the problem evolves to an equilibrium state.

- *Base Case Problem Description*

Gradients in aqueous pressure, gas pressure, and temperature are imposed across a 20-m one-dimensional horizontal domain, discretized using uniformly spaced 1-m grid cells. A horizontal domain is used to eliminate gravitational body forces from the problem, as an additional simplification. The pressure and temperature gradients are specified to yield aqueous saturation conditions in the first 10 grid cells and aqueous unsaturated conditions in the remaining 10 grid cells. The simulation then proceeds to equilibrium conditions in pressure, phase saturations, and temperature. Variable time stepping should be used to capture the flow and transport processes at early and late times during simulation. Figure 3 shows the problems schematic.

The list of processes simulated in this problem include:
1.Aqueous-gas multifluid flow subject to relative permeability, capillary effects, and phase transition from aqueous saturated to unsaturated
2. Heat transport across multifluid porous media with phase advection and component diffusion
3. Change in CH4 solubility in water with pressure and temperature
4. Change in thermodynamic and transport properties with pressure and temperature

- *Simulation Results Comparison*

Lawrence Berkeley National Laboratory, with support from NETL, developed the first publicly available model designed exclusively to simulate gas hydrate reservoir behavior and production potential (TOUGH+/HYDRATE). TOUGH+/HYDRATE is the most recent implementation of the TOUGH-Fx/HYDRATE code. In addition, NETL has released a freeware, open-source, earlier version of the code under the name HydrateResSim. MH-21 Hydrate Reservoir Simulator (MH-21 HYDRES), developed by the National Institute of Advanced Industrial Science and Technology, Japan Oil Engineering Co., Ltd. and the University of Tokyo has been specifically designed to assess production from gas hydrate deposits. The Pacific Northwest National Laboratory and the Petroleum Engineering Department at the University of Alaska, Fairbanks have modified the multi-phase simulator (STOMP) to allow for the inclusion of gas hydrates (STOMP-HYD). Also, those investigating Alaska North Slope gas hydrate resource potential as part of a BP Exploration Alaska, Inc. (BPXA) research project in collaboration with the US DOE have extended work begun at the University of Calgary and the University of Alaska-Fairbanks to apply a commercially available simulator (CMG STARS) to model production from characterized gas hydrate-bearing reservoirs.

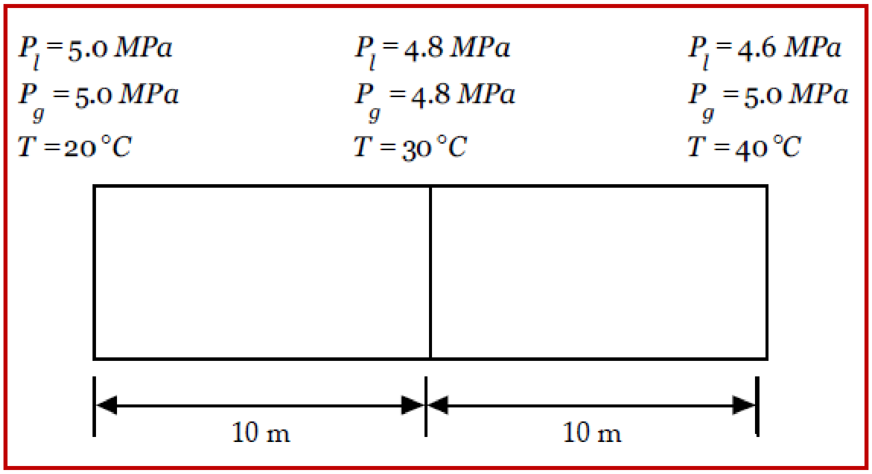


Figure 3 Problems Schematic

The results using THCM-hydrate code (our program) are compared against the outputs from the other seven codes (i.e. HydrateResSim,MH-21,stars-Mehran,STARS,STOMP-HYD,TOUGH-FX,Univ-Houston). The main comparisons are presented below in Figure 4 to 6 for the following time of analyses: day 1, day 10, day 100, day 1000, and day 10000. The comparisons are very satisfactory. Just some slight differences in terms of gas pressure are observed at the earliest stages of the analyses.

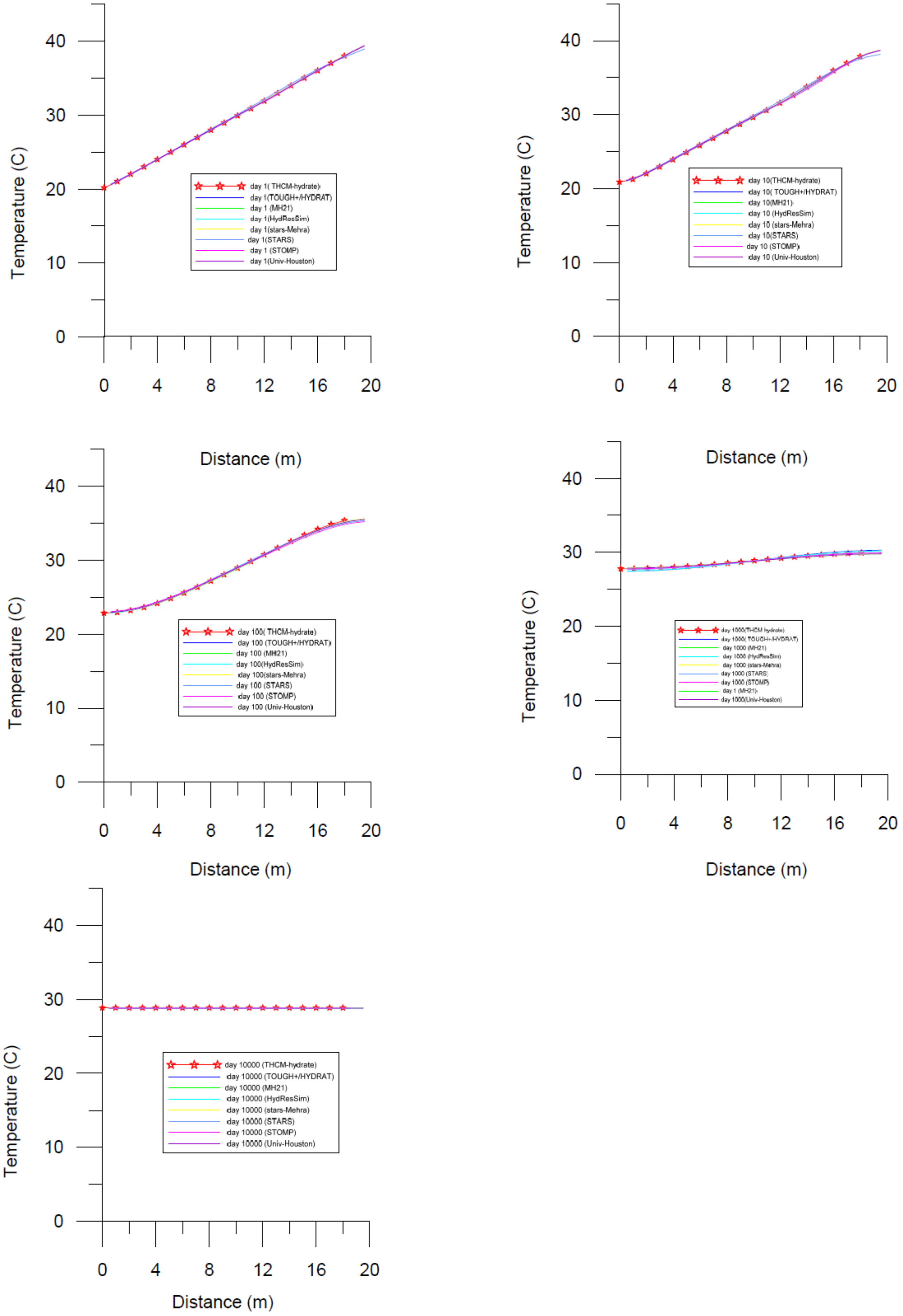


Figure 4. Temperature comparisons

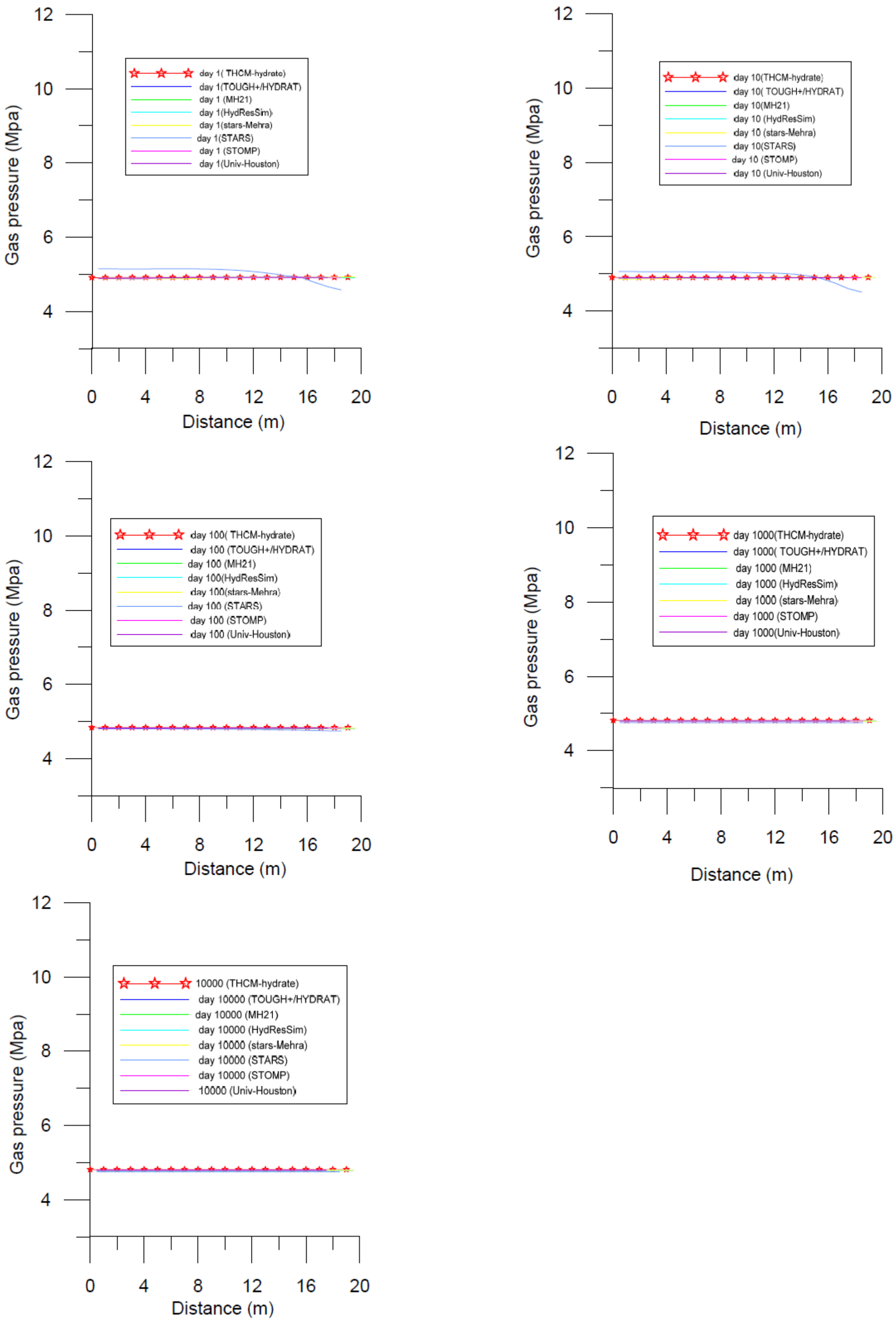


Figure 5. Gas pressure comparisons

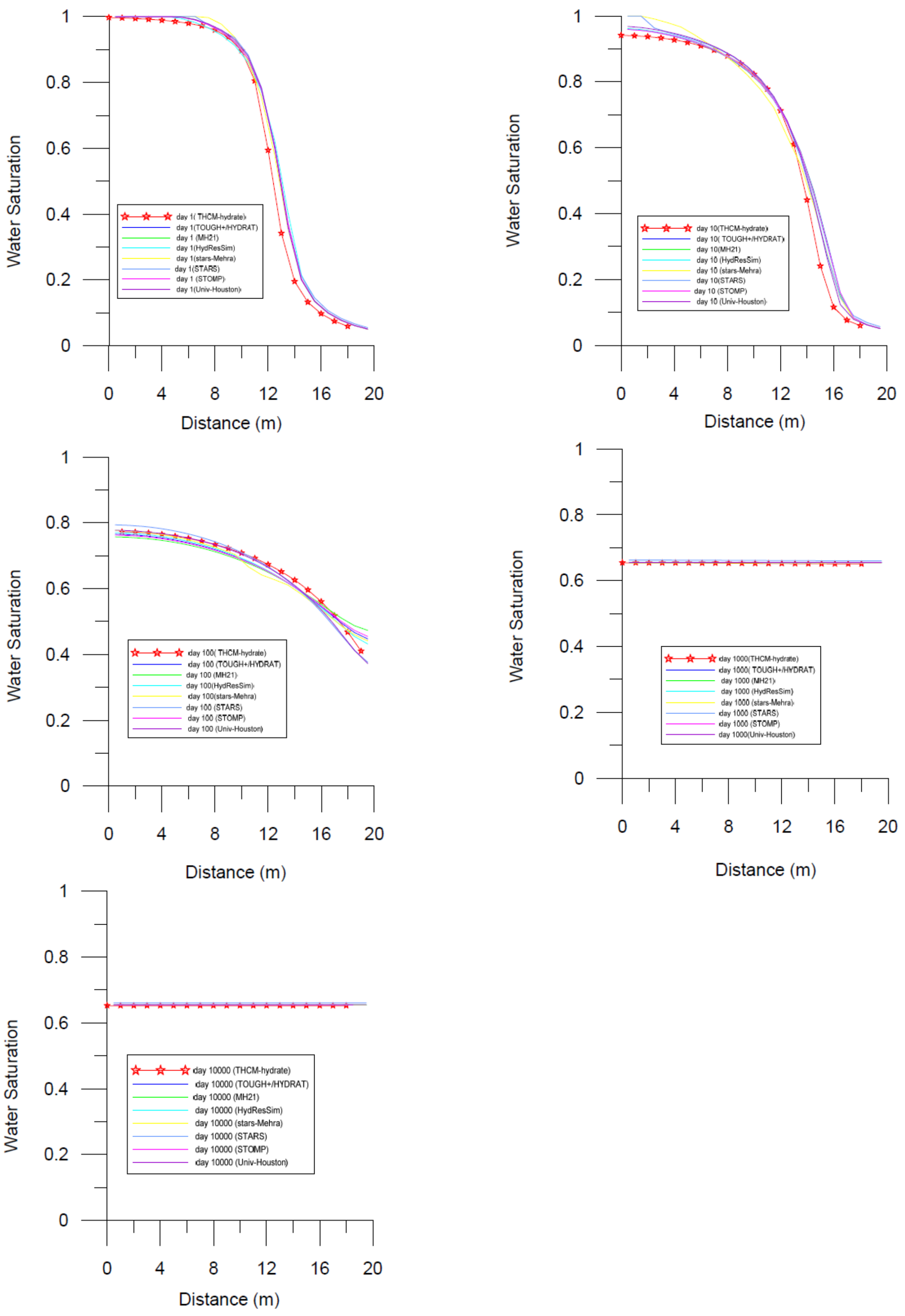


Figure 6. Water saturation comparisons

PRODUCTS

Publications – Presentations:
An abstract has been submitted to the Gordon Research Conference on Natural Gas Hydrate Systems (Galveston, Texas, March, 2014)
Title: "Numerical THCM Modeling of HBS using a truly coupled approach"

Website: Publications (for academic purposes only) and key presentations are included in
http://pmrl.ce.gatech.edu/
http://engineering.tamu.edu/civil/people/msanchez

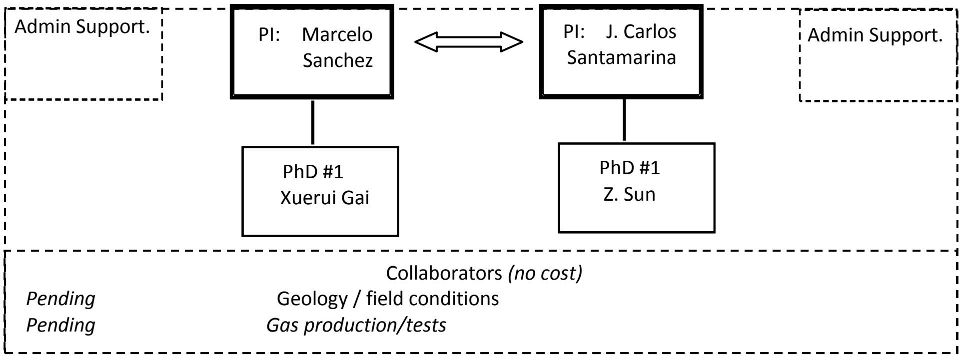
Technologies or techniques: None at this point.

Inventions, patent applications, and/or licenses: None at this point.

Other products: None at this point.

PARTICIPANTS

Research Team: The current team is shown next.



IMPACT

- While it is still too early to assess impact, we can already highlight the computational platform extensively validated in a wide range of coupled thermo-hydro-chemo-mechanical coupled problems (Code-Bright).

CHANGES/PROBLEMS:

None so far.

SPECIAL REPORTING REQUIREMENTS:

Nothing to report

BUDGETARY INFORMATION:
Cost plan report

Baseline Reporting Quarter	Budget Period 1								Budget Period 2							
	Q1		Q2		Q3		Q4		Q1		Q2		Q3		Q4	
	Enter date range 10/1/13- 01/31/14		Enter date range		Enter date range		Enter date range		Enter date range		Enter date range		Enter date range		Enter date range	
	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total
Baseline Cost Plan	$ 40,400.00	$ 40,400.00														
Federal Share	$ 40,400.00	$ 40,400.00														
Non-Federal Share	$ 14,964.00	$ 14,964.00														
Total Planned	$ 55,364.00	$ 55,364.00														
Actual Incurred Costs	$ 5,301.83	$ 5,301.83														
Federal Share	$ 3,335.02	$ 3,335.02														
Non-Federal Share	$ 5,182.96	$ 5,182.96														
Total Incurred costs	$ 8,517.98	$ 8,517.98														
Varience	$ 46,846.02	46846.02														
Federal Share	$ 1,966.81	$ 1,966.81														
Non-Federal Share	$ 9,781.04	$ 9,781.04														
Total Varience	$ 11,747.85	$ 11,747.85														

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