Numerical Studies for the Characterization of Recoverable Resources from Methane Hydrate Deposits

FP00008138

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National Energy Technology Laboratory

Oil & Natural Gas
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Objective: To develop the knowledge base and quantitative predictive capability to describe the most important processes and phenomena associated with gas production from hydrate deposits

Project Components:
- TOUGH+HYDRATE: simulator for hydrate-bearing reservoirs
- Design and evaluation of DOE and industry production tests
- Behavior of hydrates in the natural environment
- Coordinated laboratory work
- Collaborations and training

This was the 2\textsuperscript{nd} year ($400K) of a new project, FY19-FY21, part of a 20+-year DOE-funded hydrate program at LBNL
Technical Approach

FY20:

Task 6: Project Management and Planning

Task 7: Code Maintenance, Updates, and Support

Tasks 8-12: Design support for a DOE field test on the Alaska North Slope

Task 13: Support of DOE’s Field Activities and Collaborations

Task 14: Participation in the Code Comparison Study of Coupled Flow, Thermal and Geomechanical Processes

Task 15: Publications, Tech Transfer and Reporting
FY20:

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Task 15: Publications, Tech Transfer and Reporting
1. Components

(1) H₂O
(2) CH₄
(3) Hydrate (*)
(4) Salt
(5) Inhibitor
(6) Heat

(*) For kinetic dissociation

2. Phases

(1) Aqueous: H₂O, CH₄, S, I
(2) Gas: CH₄, H₂O, I
(3) Solid-Hydrate: CH₄N₄H₂O
(4) Solid-Ice: H₂O

3. P-T relationships

T+H is a fully compositional simulator capable of handling:
(a) Equilibrium or kinetic dissociation,
(b) Depressurization, thermal stimulation, inhibitor effects, and combinations

30 Possible phase combinations


TOUGH+HYDRATE Codes

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- Used by 40+ research organizations in 18 countries
- Used by 8 international oil and gas companies

LBNL and/or T+H involved in the planning/design of nearly every international field test:
- Mallik (DOE/Japan), PBU-L106 (DOE), “Mt. Elbert” Unit-D (DOE), Ignik Sikumi (DOE/ConocoPhillips), AC818/“Tigershark” (DOE/Chevron)
- Ulleung Basin (DOE/KIGAM), India NGHP-02 (DOE/India)
- Shenhu (China) (T+H code)
LBNL & The International Code Comparison Study 2

International effort comparing T-H-M simulators for gas hydrate production

- 5 test problems ranging from 0D to 1D flow to 3D T-H-M cases
- **LBNL lead Problem 4** (radially symmetric flow and geomechanics)
- Co-authors of IGHCCS2 paper

What else could we learn from this study?

- Tested **mesh convergence** for standard, Darcy-based hydrate simulation methods: are we using “correct” discretization?
- Ongoing study: more complex than expected

- **Coupled flow, geomechanics, and hydrate dissociation**
- **1D axisymmetric r-z mesh**, 5,000 m x 1 m, $\Delta r = 0.02$ m, around a well, $t = 30$ days
- Compare depressurization to an **analytical solution** (Rudnicki, 1986)

\[
P = \frac{Q_S/h}{4\pi k/\eta} E_1(\xi(r,t))
\]

\[
u_r = \frac{(Q_S/h)\alpha f(\xi(r,t))r}{8\pi(k/\eta)(K_d + 4G/3)}
\]
International effort comparing T-H-M simulators for gas hydrate production

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**What else could we learn from this study?**

- Tested **mesh convergence** for standard, Darcy-based hydrate simulation methods: are we using “correct” discretization?
- Ongoing study: more complex than expected

- Very close match between TOUGH+HYDRATE/Millstone and the analytical solution
- Other IGHCCS2 codes performed well, too
Test Mesh Convergence in 1D Case

- 50% hydrate (initial)
- Scale discretization ($\Delta r$) by factor $S$
- $S = 1.0-10.0 \rightarrow \Delta r = 0.02 \text{ m} - 0.2 \text{ m}$
- Good convergence even for coarser meshes
- Some lensing appears at $S = 2.0$ ($\Delta r = 0.04 \text{ m}$)

A Challenge: 70% Hydrate

- Lower effective permeability
- $S = 1.5 - 20 \rightarrow \Delta r = 0.03 \text{ m} - 0.4 \text{ m}$
- Lensing appears at $S < 10.0$
- $u_r$ varies with lensing ($S_H$ vs. $P$)
- Lensing sensitive to initial heterogeneity and $k_{eff}$
2D Mesh Convergence Study

- 1D N-element axisymmetric $\rightarrow$ N x N 2D
- Scale S from 2.0 to 50.0 ($\Delta x/\Delta y$ → 4 cm to 1 m)
- Geomechanics disabled
- Does the simulation still match axisymmetric behavior?

- $S = 2.0$, 50% hydrate, 1D r-z vs. 2D x-y
- Mild lensing seen in both (4-7 m)
- Water and gas production similar
- Clue: small variation w/o geomechanics

![2D Model (Top down)](image)

![S = 20.0](image)
![S = 12.0](image)
![S = 5.0](image)
![S = 2.0](image)

![1D t = 30 d](image)

![2D t = 30 d](image)
2D Discretization

70 % Hydrate, 30 days
2D Discretization

- Lensing clearly initiated by mesh features (would 2D $r$-$\theta$ meshes look different?)
- Radially symmetric features appear by 30 days, larger $r$
- “Moving lenses” and “wormholing” that appear in earlier studies develop
- Discretization geometry around the well critical in seeding heterogeneity
- Mild lensing doesn’t affect prediction of net production rates
Conclusions and Questions

• Investigation ongoing (part of FY21/BP3 Tasks 18 and 19)

• Treatment of heterogeneity and lensing must be understood
  • Effect of geomechanics?
  • Focus: kinetic vs. equilibrium when mesh scale varies greatly within a simulation

• Effect on predicting overall production in 2.5D and 3D systems?
  • More and more detail in geological models
  • System evolution vs. system productivity?
  • Numerics vs. physics?

• Core-scale studies and laboratory verification

• Close attention to $k_{rel}$ and $k_{eff}$ (real data)
Design support for a DOE field test on the Alaska North Slope

- Assess the feasibility of production via numerical simulation
- Determine viable production strategies

Need Geological Model
- System stratigraphy and geometry
- Reservoir boundaries, faults and aquifers
- Geologic model and data provided by project management and collaborators
Design support for a DOE field test on the Alaska North Slope

Comments on Flow System of Unit B

- Significant variability of $k$, $S_H$, $S_{irA}$
- Remarkable consistency of $k_{int}-S_{irA}$ relationship in the hydrate units
- $k_{rel}$: $n_{min}$ from core studies vs. $n_{max}$ from NMR studies
- We maintain maximum fidelity to data: properties and conditions layer by layer in the HBZ
- BOUNDARIES: Duration of test is 12-18 months

Unit B: Very desirable properties ($k_{int}$, $\phi$, $n$)

- Top boundary of simulated domain: top of Unit D above
- Bottom boundary of simulated domain: bottom of available dataset
- Radial/lateral boundary: at $r = 800$ m
- Flows across boundaries continuously monitored
Design support for a DOE field test on the Alaska North Slope

- Cylindrical system, vertical well
  - Within Unit B: $\Delta z = 0.1$ m
  - Within Units C and D: $\Delta z = 0.25$ m
  - Within the rest of domain: $\Delta z$ variable (log, 2-sided)
  - Radial: $\Delta r$ from 0.1 to 0.25 m for $r < 100$ m, log distribution to $r = 800$ m
- Dimension $641 \times 343$ (r, z) = **220K elements**, 880K eqs
- Every vertical subdivision/layer is considered a separate rock type with unique properties
- Properties derived from the team database
- All boundaries: permeable/flowing, monitored

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**Initial Conditions**

- $P/T$ distribution (from Myshakin, personal communication)
- Initial saturations and spatial distribution (from database)
- Salinity of water: 0.5% (from database)
- Account for salinity in simulations (useful indicator)
Design support for a DOE field test on the Alaska North Slope

• Assess the feasibility of production via numerical simulation
• Determine viable production strategies

• Reference case:
  • Perforated interval: **10 m at top of formation**
  • BHP management: 2 MPa below $P_0$, **2 MPa decline every 30 days**, until $P_{\text{final}} = 2.8$ MPa
  • Anisotropy: $k_r/k_z = 10$
  • $k_{\text{rel}}$: Obtained from $n_{\text{min}}$ (OPM)

• Exploratory cases:
  • Assess $k_{\text{rel}}$: low $k_{\text{eff}}$, $n_{\text{max}}$
  • Vary length of perforated interval 5 m, 15 m, etc.
  • “Low well”: **10 m interval 3 m below top of formation**
Generation of gas by dissociation: weak
Production rate: **flat to declining after 60 days!** (Especially gas rate)
Water production: increasing, water production $\approx$ water infiltration
Monitoring wells: show pressure recovery/weak depressurization
Alaska North Slope: Reference Case

Unit B: Hydrate-bearing zone, r = 0 - 40 m

- Limited range of depressurization
- Dissociation focuses at top of HBZ
- Limited formation of gas → limited gas production
Alaska North Slope: Improved

Attempted improvement:
• Move production interval 3 m down into hydrate zone ("low well")
• Maintain stepped depressurization, use most-likely properties ($k_{rel}$)

- Increased hydrate dissociation/gas generation (~3X)
- Increased gas production at well (~2.5X)
- Production plateau after 60 days, but at a higher level
- Water production still high, but lower than reference case
Alaska North Slope: Improved

- Stronger depressurization, more extensive
- Dissociation focused at core of HBZ
- Low-$k_{\text{eff}}$ hydrate zones “encase” depressurized zone
- Increased formation of gas $\rightarrow$ increased gas production
Significant \( \text{H}_2\text{O} \) production and inefficient depressurization because of significant/persistent \( \text{H}_2\text{O} \) inflows

Placement of the top of the well 3 m below the top of the target results in consistently optimal performance in all reservoir property cases

- Higher gas production due to more effective depressurization
- The most-likely permeability/relative permeability scenario has the best performance
- Effect of \( k, n, k_{\text{rel}} \): Significant in terms of gas and \( \text{H}_2\text{O} \) production, not so in terms of water-to-gas ratio (defines the envelope of possible production estimates)
- Production interval length, anisotropy have a minor/negligible effect
- Under this geological model, water production is a pervasive issue
- Simulations to be updated/expanded as data evolves
Tech Transfer and Reporting

4 publications

Journal Articles:

Conference Papers:

6 presentations:

Postponed:
FY20-21 Tasks

Task 16: Project Management and Planning ($5K)

Task 17: Continuation of the Baseline Study for a DOE field test on the Alaska North Slope ($310K)

Task 18: Code Maintenance, Updates, and Support ($60K)

Task 19: Support of DOE’s Field Activities and Collaborations ($5K)
  • IGHCCS2 Completion and Publication

Task 20: Tech Transfer and Reporting ($10K)
Task 21: Publications and Travel ($10K)
Accomplishments to Date

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Appendix
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<thead>
<tr>
<th>Milestone Title</th>
<th>Milestone Description</th>
<th>Planned Completion Date</th>
<th>Actual Completion Date</th>
<th>Status / Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deliverable</td>
<td>Updated versions serial and parallel versions of the T+H/Millstone code</td>
<td>July 31, 2020</td>
<td>Ongoing</td>
<td>Ongoing</td>
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<tr>
<td>Deliverable</td>
<td>Updates reports and publications related to DOE international collaborations</td>
<td>September 30, 2020</td>
<td>November 21, 2019</td>
<td>Paper on India studies appeared in print (JMPG)</td>
</tr>
<tr>
<td>Deliverable</td>
<td>Completion of participation in the code comparison study; contributions to reports and publications</td>
<td>September 30, 2020</td>
<td>June 30, 2020</td>
<td>Paper accepted for publication (JMPG). Conference paper submitted (postponed).</td>
</tr>
<tr>
<td>Deliverable</td>
<td>Publications, Tech Transfer, Travel, and Reporting</td>
<td>Quarterly</td>
<td>Quarterly</td>
<td>Q1 and Q2 reports submitted</td>
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