Development of Advanced Thermal-Hydrological-Mechanical-Chemical (THMC) Modeling Capabilities for Enhanced Geothermal Systems

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Colorado School of Mines

Project Officer: Dr. Bill Vandermeer
Total Project Funding: $1,633,493
April 24, 2013

This presentation does not contain any proprietary confidential, or otherwise restricted information.
Overview

• Timeline

<table>
<thead>
<tr>
<th>Start Date</th>
<th>End Date</th>
<th>Complete</th>
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</thead>
<tbody>
<tr>
<td>01/01/10</td>
<td>12/31/2013</td>
<td>90%</td>
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• Budget

<table>
<thead>
<tr>
<th>Contributor</th>
<th>Fund</th>
</tr>
</thead>
<tbody>
<tr>
<td>Department of Energy (DOE)</td>
<td>$1,191,893</td>
</tr>
<tr>
<td>Computer Modeling Group Ltd. (CMG)</td>
<td>$441,600</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$1,633,493</strong></td>
</tr>
</tbody>
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• Partners

Colorado School of Mines
Lawrence Berkeley National Laboratory
Computer Modeling Group Ltd.
Relevance/Impact of Research

• The reservoir simulator developed from this project is among the first rigorous fully couple hydro-thermal-mechanical-chemical (THMC) reservoir simulator in public domain.

• This simulator will substantially enhance our ability to characterize EGS systems and provide practical approaches to assess the following:
  • Long-term performance
  • Optimum design
  • Operation strategies, and
  • Commercial feasibility
Project Objectives

- **Develop a general framework** for effective flow of water, steam and heat in porous and fractured geothermal formations
- **Develop a computational module** for handling coupled effects of pressure, temperature, and induced rock deformations
- **Develop a reliable model** of heat transfer and fluid flow in fractured rocks
- **Develop a chemical reaction module** to include important chemical reactions in EGS
- **Develop an efficient parallel computing** methodology for simulation purposes
- **Apply the EGS simulator** to laboratory and field data of geothermal reservoirs.
Scientific/Technical Approach

General framework: Integral finite differences

\[
\frac{d}{dt} \int_{V_n} M \, dV_n = \int_{\Gamma_n} F \cdot n \, d\Gamma_n + \int_{V_n} q \, dV_n
\]

Mass balance equation for Component $\kappa$

\[
M^\kappa = \sum_{\beta} \phi S_\beta \rho_\beta X^\kappa_\beta
\]

\[
F^\kappa_\beta = \sum_{\beta} X^\kappa_\beta v_\beta
\]

\[
v_\beta = -k_{r\beta} \frac{\rho_\beta}{\mu_\beta} (\nabla P_\beta - \rho_\beta g)
\]

Energy balance equation

\[
M^h = (1 - \phi) \rho_R C_R T + \phi \sum_{\beta} S_\beta \rho_\beta u_\beta
\]

\[
F^h = -\left[ (1 - \phi) K_R + \phi \sum_{\beta} S_\beta K_\beta \right] \nabla T + f_\phi \sigma_0 \nabla T^4 + \sum_{\beta} h_\beta F^\kappa_\beta
\]

Force balance equation

\[
M = 0
\]

\[
F = \frac{3(1 - \nu)}{(1 + \nu)} \nabla \tau_m + F_b - \frac{2(1 - 2\nu)}{(1 + \nu)} \nabla \left[ \sum_j \alpha_j p_j + 3\beta K \omega_j T_j \right]
\]
Scientific/Technical Approach

Rock deformation module

- Fully-coupled geomechanics and flow modules based on poro-thermo- thermo-elastic assumptions

- Force balance equation:

$$\int_{\Gamma_n} \left[ \frac{3(1 - \nu)}{(1 + \nu)} \nabla \tau_m + F_b - \frac{2(1 - 2\nu)}{(1 + \nu)} \nabla \sum_j \left( \alpha_j p_j + 3 \beta K \omega_j T_j \right) \right] \cdot \mathbf{n} d\Gamma_n = 0$$

$$K \varepsilon_v = \tau_m - \sum_j \left( \alpha_j p_j + 3 \beta K \omega_j (T_j - T_{ref}) \right)$$
Scientific/Technical Approach

Rock deformation module

• Stress-sensitive hydraulic properties
  – Four correlations for porosity-stresses and
  – Four correlations for permeability-stresses are implemented

For example:

\[ \tau'_m = \tau_m - \alpha p \]

\[ \phi = \phi(\tau'_m) \]

\[ \phi_f = \phi_f(\tau'_m) \]

\[ k = k(\tau'_m) \]

\[ k_{fi} = k_{fi}(\tau'_m) \]

\[ P_c = P_{c0}\left(\frac{\sqrt{k_i / \phi_i}}{\sqrt{k / \phi}}\right) \]

Chemical reaction module

- Aqueous-based reservoir stimulation is likely to promote dissolution of some rock minerals, while precipitating others, and lead to large impact on the permeability of the fracture network.

- Mineral dissolution and precipitation are considered under kinetic conditions and the temperature dependence of the reaction rate constant can be expressed via an Arrhenius equation.

- **Transport equations**: Mass balance (transport) equations for chemical components can be expressed as:

\[
\frac{d}{dt} \int_{V_n} M^\kappa \, dV_n = \int_{\Gamma_n} F^\kappa \cdot nd\Gamma_n + \int_{V_n} q^\kappa \, dV_n + \int_{V_n} R^\kappa \, dV_n
\]

where \( \kappa \) is chemical component index, such as \( \text{Ca}^{2+}, \text{SiO}_2(aq) \), and \( R \) is mass transfer from solid phases such as calcite and silica mineral dissolution and precipitation.

- Chemical reactions are considered as secondary equations.
Scientific/Technical Approach

Fracture module

- Generalized dual-continuum methodology: treats fracture and matrix flow and interactions using a multi-continuum numerical approach

- The Approach can be applied for
  - Discrete fracture i.e. hydraulic fracture (man made) and faults
  - Fracture network or naturally fractured reservoirs
Parallel computing module

- Advanced parallel simulation scheme has been developed and implemented into TOUGH2-EGS simulator.

- Considering the highly nonlinear nature of the coupled processes as well as the large number of mass/chemical components, involved in multiphase fluid and heat flow in EGS systems, efficient parallel computation is an essential step for any realistic field-scale application of reservoir modeling tools (Zhang et al. 2001a, Zhang and Wu, 2006).

- The parallel simulation capability has been built by taking advantage in rapid advance in computer and computational sciences, as well as high-performance reservoir simulation technology (Wu et al. 2002; Zhang et al. 2008).
Accomplishments, Results and Progress

• Developed simulators
  – TOUGH2-EGS (THMC for single CPU)
  – TOUGH2-EGS-MP (THM for multiple CPUs)

• Published seven conference papers

<table>
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<tr>
<th>Original Planned Milestone</th>
<th>Technical Accomplishment</th>
<th>Date Completed</th>
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<tbody>
<tr>
<td>Verify the developed simulators against:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Analytical solutions</td>
<td>Completed</td>
<td>Q2 2011</td>
</tr>
<tr>
<td>• Commercial simulator</td>
<td>Completed</td>
<td>Q3 2011</td>
</tr>
<tr>
<td>• Published simulation study</td>
<td>Completed</td>
<td>Q1 2012</td>
</tr>
<tr>
<td>• Field data</td>
<td>Completed</td>
<td>Q4 2012</td>
</tr>
<tr>
<td>Public training</td>
<td>June 2-3, 2013</td>
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</table>
Verification: Against analytical solutions

1-D Heat Conduction in Deformable Media (Jaeger et al., 2007)

1-D Consolidation (Terzaghi et al., 1996)
Verification: Against CMG-STAR (commercial simulator)

Matrix block size = 50 m.

Matrix block size = 250 m.

Heat Sweep in a Vertical Fracture

No heat gain from surrounding rock

With heat gain from surrounding rock
Verification: Against published simulation study (Induced-MEQ study the Geysers, Rutqvist et al., 2006)

Schematic of model geometry for coupled THM modeling of steam production at the Geysers Geothermal Field

Verification: Against published simulation study (Induced-MEQ study the Geysers, Rutqvist et al., 2008)

Schematic of model geometry for coupled THM modeling of steam production and water injection at the Geysers Geothermal Field

TOUGH2-EGS results

Rutqvist et al. (2008) results

References


Verification: Against field data

The injection index comparison between field data and simulation results: The well injection index increased with time indicates well stimulation due to cold water injection which can be captured by the simulation.
THMC application example

Results: Mean stress profiles

Results: Mineral volume fraction changes at the vicinity to the injector

Results: Fracture aperture change due to stress and chemical reaction effects
### Future Directions

Complete the following list:

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Expected Completion Date</th>
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<tr>
<td>User’s manual</td>
<td>Q1 2013</td>
</tr>
<tr>
<td>Speed up test for large problems (&gt;1,000,000 grids)</td>
<td>Q2 2013</td>
</tr>
<tr>
<td>Public training</td>
<td>Q2, 2013</td>
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<tr>
<td>Final report</td>
<td>Q3 2013</td>
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We have successfully developed a fully-coupled hydro-thermal-mechanical-chemical (THMC) reservoir simulator and validated the simulator against analytical solution, a commercial reservoir simulator, published simulation study, and field data.

The reservoir simulator developed from this project is among the first rigorous fully-coupled hydro-thermal-mechanical-chemical (THMC) reservoir simulator.

The developed simulators can be used to characterize EGS systems and provide practical approaches to assess the following:

- Long-term performance
- Optimum design
- Operation strategies, and
- Commercial feasibility

The overall project is largely on schedule and budgeted appropriately.
### Timeline:

<table>
<thead>
<tr>
<th></th>
<th>Planned Start Date</th>
<th>Planned End Date</th>
<th>Actual Start Date</th>
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### Budget:

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<tr>
<th></th>
<th>Federal Share</th>
<th>Cost Share</th>
<th>Planned Expenses to Date</th>
<th>Actual Expenses to Date</th>
<th>Value of Work Completed to Date</th>
<th>Funding needed to Complete Work</th>
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<tr>
<td></td>
<td>$1,191,893</td>
<td>$441,600</td>
<td>$992,917</td>
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<td>$199,976</td>
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- A collaborated study with a geothermal field operator is on going
- Public training for the developed simulator is planned during June 2-3, 2013
List of Publications


