Numerical Simulation of Critical Factors Controlling Heat Extraction from Geothermal Systems Using a Closed-Loop Heat Exchange Method

Curtis M. Oldenburg¹, Lehua Pan¹, Mark P. Muir², Alan D. Eastman², Brian S. Higgins²

¹Energy Geosciences Division
Lawrence Berkeley National Laboratory

²Greenfire Energy

February 24, 2016
Overview

- Closed loop geothermal energy extraction avoids need to handle reservoir fluids
- There are various configurations of closed loop system
  - Single-well U-tube placed in perforated casing
  - Tube-in-tube with insulated central tube
- Prior studies showed poor performance due to limited convective heat transfer
- Recent developments in drilling technology, novel working fluids, and need for renewables are creating new interest in closed-loop systems
- Here we consider a single U-shape configuration with long horizontal section in the reservoir and with CO$_2$ as the working fluid.
- We analyze this system using TOUGH2 with wellbore flow capability (T2Well)
- Modeling capability is described along with critical factors controlling performance.
  - Reservoir permeability
  - CO$_2$ temperature
  - Flow rate
  - Pipe diameter
  - Water vs. CO$_2$ as working fluid
The well is U-shaped with specified injection rate and constant pressure at the production wellhead. 

CO₂ at P = 7 MPa, T = 75 °C

Total length: 6100 m
Vertical: 2 X 2500 m
Horizontal: 1100 m

Semianalytical solution (Ramey, 1961) to calculate the conductive heat exchange between well and formation.

Within the reservoir, heat exchange to pipe is from 3D porous media (conduction and convection) or optionally by semianalytical solution (“well-only”).
We use an integrated wellbore (pipe) and porous media (reservoir) system and exploit symmetry of the system.

- Half of domain is gridded to exploit mirror-plane symmetry.

- The vertical wells are connected to the horizontal well at two ends.

- The heat exchanges between the vertical wells and the surrounding formation is by conduction (semi-analytical heat exchange).

- There are a total of 10,543 grid cells and 31,364 connections.
We considered three different cases with different permeabilities.

### Permeability (m\(^2\))

<table>
<thead>
<tr>
<th>Zone</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Reservoir</td>
<td>10(^{-18})</td>
<td>10(^{-12})</td>
<td>10(^{-12})</td>
</tr>
<tr>
<td>Stimulated zone</td>
<td>10(^{-18})</td>
<td>10(^{-12})</td>
<td>10(^{-10})</td>
</tr>
<tr>
<td>Underlying &amp; overburden</td>
<td>10(^{-20})</td>
<td>10(^{-15})</td>
<td>10(^{-15})</td>
</tr>
</tbody>
</table>

40 m x 40 m stimulated zone around the horizontal well.
We chose typical properties for the system

Table 1. Properties of the (6-inch diameter) well.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal well (lateral)</td>
<td>1100 m</td>
<td></td>
<td>Length</td>
</tr>
<tr>
<td>Diameter</td>
<td>0.168 (6.61 inch) m</td>
<td></td>
<td>Diameter</td>
</tr>
<tr>
<td>Tube I.D.</td>
<td>0.154 (6.06 inch) m</td>
<td></td>
<td>Material</td>
</tr>
<tr>
<td>Steel</td>
<td>Steel</td>
<td></td>
<td>Roughness factor</td>
</tr>
<tr>
<td>Roughness factor</td>
<td>4.57x10^{-5} m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical sections of well:</td>
<td>2500 m</td>
<td></td>
<td>Length</td>
</tr>
<tr>
<td>Diameter</td>
<td>0.168 (6.61 inch) m</td>
<td></td>
<td>Diameter</td>
</tr>
<tr>
<td>Tube I.D.</td>
<td>0.154 (6.06 inch) m</td>
<td></td>
<td>Material</td>
</tr>
<tr>
<td>Steel</td>
<td>Steel</td>
<td></td>
<td>Roughness factor</td>
</tr>
<tr>
<td>Roughness factor</td>
<td>4.57x10^{-5} m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Properties of various regions of the closed-loop reservoir model.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Thickness (m)</th>
<th>Porosity (vol %)</th>
<th>Rock grain density (kg m^{-3})</th>
<th>Rock grain specific heat (J/kg °C)</th>
<th>Thermal cond.* (W/(m °C))</th>
<th>Pore compress. (Pa^{-1})</th>
<th>k (Case 1) (m^2)</th>
<th>k (Case 2) (m^2)</th>
<th>k (Case 3) (m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overburden</td>
<td>155</td>
<td>5</td>
<td>2700</td>
<td>1000</td>
<td>4.0</td>
<td>7.25 x 10^{12}</td>
<td>10^{-20}</td>
<td>10^{-15}</td>
<td>10^{-15}</td>
</tr>
<tr>
<td>Reservoir</td>
<td>158</td>
<td>25.4</td>
<td>2700</td>
<td>1000</td>
<td>4.0</td>
<td>7.25 x 10^{12}</td>
<td>10^{-18}</td>
<td>10^{-12}</td>
<td>10^{-12}</td>
</tr>
<tr>
<td>Underburden</td>
<td>55</td>
<td>5</td>
<td>2700</td>
<td>1000</td>
<td>4.0</td>
<td>7.25 x 10^{12}</td>
<td>10^{-20}</td>
<td>10^{-15}</td>
<td>10^{-15}</td>
</tr>
<tr>
<td>High-k zone around well</td>
<td>40</td>
<td>25.4</td>
<td>2700</td>
<td>1000</td>
<td>4.0</td>
<td>7.25 x 10^{12}</td>
<td>10^{-18}</td>
<td>10^{-12}</td>
<td>10^{-10}</td>
</tr>
</tbody>
</table>

*under liquid-saturated conditions.
All simulations are carried out with T2Well /ECO2N

- T2Well is a version of TOUGH2 that allows full coupling of a wellbore to the porous media reservoir.
- Momentum equation is solved for wellbore flow with the drift-flux model to handle two-phase momentum transfer.
- ECO2N models thermophysical properties of CO₂, water, and salt.

Reference:


<table>
<thead>
<tr>
<th>Components</th>
<th>H₂O, CO₂, and NaCl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (MPa)</td>
<td>Up to 60</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>3 - 300</td>
</tr>
<tr>
<td>Salinity</td>
<td>0 to fully saturated</td>
</tr>
<tr>
<td>Salt can precipitate or dissolve</td>
<td>yes</td>
</tr>
<tr>
<td>Salt can alter porosity and permeability</td>
<td>yes</td>
</tr>
</tbody>
</table>
Temperature in the full 3D model shows signature of convective cooling around the pipe for Case 2

Effect of convection is significant. Cold plume expands preferentially downward.
Convection strongly enhances energy gain, but thermal conduction is also effective in heating the pipe.

“Well-only” (semi-analytical heat transfer) matches the low-k Case 1 (~conduction only).

$\text{CO}_2$ absorbs heat from surrounding formation in most of the injection section and all of the horizontal section, while losing heat in the upper-most portion of the production well.
CO₂ compresses only in the injection well and the first part of the horizontal well.

Temperature increases as CO₂ compresses and decreases as it expands. Such effects increase with time due to cooling of the formation surrounding the injection well which causes less heat gain resulting in higher density.
Velocity decreases in the injection well due to increases in density and then it increases as CO$_2$ enters the horizontal well.

Velocity reaches its maximum at the production wellhead. Both kinetic energy and friction heat increase with velocity.
Pressure increases in the injection well and decreases in the horizontal and production wells

Larger pressure gradient in the production well than in the injection well reflects the impact of much higher friction pressure loss due to higher velocity in the production well.
Lower initial CO$_2$ temperature enhances energy gain by increasing $\Delta T$ between reservoir and pipe.
Higher flow rate enhances energy gain up to a point, and then it diminishes because the fluid is hotter initially.
Larger diameter pipe enhances energy gain and leads to higher temperature of produced CO$_2$. 

![Energy Gain and Production Temperature Graphs](image)
Water extracts more heat than CO₂ at same flow rate, but CO₂ is hotter and at higher pressure at exit

- H₂O is more efficient in extracting heat because it has a lower temperature due to lack of compression-heating in the injection well and because of its high heat capacity.
- However, H₂O has lower production wellhead temperature which may require use of binary system which could reduce recoverable energy relative to CO₂.
For some values of injection rate, a thermosiphon can be set up with no need for pumping.
Summary

• T2Well/ECO2N simulations of a closed-loop geothermal system have been presented.
• Sensitivity of results to various properties informs how system will perform.
• Conduction-only heat extraction is about 1.5-2 MW at 60 kg/s.
• Conduction and convection ($k_{\text{res}} = 1$ Darcy) energy extraction is approximately the same as conduction-only.
• Reservoir permeability is a primary control on energy gain.
• Stimulation to (100 Darcies) of a 40 m x 40 m region around the wellbore allows heat extraction of ~3.5-4 MW.
• Thermosiphon can be sustained with a flow rate of about 25 kg/s in a 6-inch pipe with 35 ºC CO$_2$.
• Because of compressibility, the energy gain by flowing CO$_2$ in the pipe is a complicated function of initial temperature, flow rate, and pipe diameter => iTOUGH2 optimization suggested
Acknowledgements

Support for this work was provided by GreenFire Energy. Additional support was provided by the Assistant Secretary for Fossil Energy (DOE), Office of Coal and Power Systems, through the National Energy Technology Laboratory (NETL), and by Lawrence Berkeley National Laboratory under Department of Energy Contract No. DE-AC02-05CH11231