Design, Simulation and Evaluation of a Doublet Heat Extraction Model in Enhanced Geothermal Systems

Yidong Xia¹, Mitchell Plummer¹, Earl Mattson¹, Rob Podgorney¹, and Ahmad Ghassemi²

¹Idaho National Laboratory, Idaho Falls, Idaho, USA
²University of Oklahoma, Norman, Oklahoma, USA

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Modeling & Simulation of EGS Heat Extraction – Brief Overview of Recent Works

• Conceptual design of EGS heat production process
  – Five-spot well layout
  – Horizontal doublet well layout
  – Triplet well layout
    Jiang et al. In Energy, 72, 300-310 (2014)
  – Comparative study between doublet, triplet, and five-spot well layouts
  – Sensitivity study of design parameters in a double well EGS

• Case dependent
  – E.g., USA, Australia, New Zealand, UK, Poland, Japan
A Two-Fold Obligation to Support the Conceptual EGS Design at INL

- Quick workflow of computer-aided EGS design & validation
- Cross-disciplinary applications, e.g.,
  - Nuclear engineering
  - Students’ research
An Industrial-Scale Conceptual Model

- 30 ~ 40 equidistant large fractures connecting two 1km long parallel well sections with a well separation of about 500m*
- Operate at least 25 years at a flow rate of 0.1 m³/s; Electric power output 5 ~ 10 MW, and pumping power < 1 MW*

**Question 1**: Realistic? **Question 2**: Achievable?
Design Constraints on Well Layout

- Equidistant fracture horizontal interval, $d_h$
  - Effect of inter-fracture interference
- Well horizontal deviation angle, $\alpha$
  - Practical alternative solution for deep drilling

V.S.

$\alpha = 0^\circ$

Five fractures – the minimum number required

$\alpha = 45^\circ$
Design Constraints on Reservoir Conditions

• Properties that affect the out electric power rate and lifespan (some are pre-tuned to preferable values)
  – Geothermal gradient (65K per km depth, Snake River Plain, Idaho)
  – Depth (restricted by rock stress)
  – Permeability, porosity, thermal conductivity, etc.

• Operational parameters
  – Stimulation/fracturing process not included in this work
    • Assume constant mechanical properties during heat production
    • Reasonable estimation of minimum heat production rate
  – Temperature of injected/produced fluid
  – Injection flow rate
  – Conversion efficiency from thermal energy to electric power
Geometries, Meshes, BCs, and ICs

Production BCs: fixed $P = 30$ MPa, heat outflow

Injection BCs: fixed $T = 80^\circ$ C, fixed flow rate

Mixed-dim model:
2D fractures
3D rock matrix

Mesh size:
111,160 elements
118,579 points

Reference depth:
$z_{\text{ref}} = -3$ km

Reservoir temp.:
$T = 203.75^\circ$ C

Thermal gradient:
$65^\circ$ C / km depth

(a) Production BCs: fixed $P = 30$ MPa, heat outflow
(b) 2D planar geometry
(c) 3D rock matrix

(a) Injection BCs: fixed $T = 80^\circ$ C, fixed flow rate
(b) Production wellbores
(c) Injection wellbores
## Material Properties

- Dual-porosity/permeability/thermal-conductivity fracture-matrix reservoir
- Fully-saturated, isotropic and homogeneous

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of the rock</td>
<td>2700 kg/m³</td>
</tr>
<tr>
<td>Density of the fluid</td>
<td>Computed from IAPWS-97</td>
</tr>
<tr>
<td>Viscosity of the fluid</td>
<td>Computed from IAPWS-97</td>
</tr>
<tr>
<td>Permeability of the matrix zone</td>
<td>1.0×10⁻²⁰ m²</td>
</tr>
<tr>
<td>Permeability of the fractured zone</td>
<td>0.5×10⁻¹² m²</td>
</tr>
<tr>
<td>Porosity of the matrix zone</td>
<td>0.01</td>
</tr>
<tr>
<td>Porosity of the fractured zone</td>
<td>0.1</td>
</tr>
<tr>
<td>Specific heat capacity of the matrix zone</td>
<td>790 J/(kg·K)</td>
</tr>
<tr>
<td>Specific heat capacity of the fluid</td>
<td>4818 J/(kg·K)</td>
</tr>
<tr>
<td>Medium average thermal conductivity of the matrix zone</td>
<td>3.0 W/(m·K)</td>
</tr>
<tr>
<td>Medium average thermal conductivity of the fractured zone</td>
<td>1.5 W/(m·K)</td>
</tr>
</tbody>
</table>
Base Test Case \((d_h = 30\, \text{m}, \alpha = 0^\circ, q'_w = 3.14\, \text{kg/s})\)

A 30-year evolution of cooled regions

Evolution of \(T_{\text{pro}}\) \((^\circ\, \text{C})\) per fracture

Evolution of \(Q_{\text{eff}}\) \((\text{MW})\) per fracture
Performance Assessment of Heat Production

- **Thermal energy production rate** per fracture, $Q_{pro}$ (kg/s),
  \[ Q_{pro} = \int_{A_b} \left( T_{pro} - T_{inj} \right) q_E \cdot n \ d\Gamma \]
  - $A_b$ – area of production boundary
  - $T_{pro} - T_{inj}$ – temperature difference between produced and injected water
  - $q_E$ – flow speed × specific heat capacity of water

- **Effective output electric power** per fracture, $Q_{eff}$
  \[ Q_{eff} = c_{eff} Q_{pro} \]
  - $c_{eff} = 10\%$ – an approximate ratio of conversion efficiency

- **Lower limit of effective temperature of produced fluid**
  - No electric power could be generated when $T_{pro}$ drops below 160°C
Base Test Case

• Stable stage from $0^{th}$ to $13^{th}$ year (per fracture data)
  – $T_{\text{pro}} \geq 203.75^\circ \text{C} \mid Q_{\text{eff}} \geq 0.165 \text{ MW}$

• Decline stage from $14^{th}$ to $30^{th}$ year (per fracture data)
  – $T_{\text{pro}} \rightarrow 176 \sim 188^\circ \text{C} \mid Q_{\text{eff}} \rightarrow 0.125 \sim 0.14 \text{ MW (12.7\% \sim 22.4\%)}$

• Validation through code comparison
  – By M. Plummer using COMSOL

• Upscale from the least-performing fracture #3 to a full-size system with 40 fractures
  – $Q_{\text{eff}} \text{ (gross)} \approx 5.6 \text{ MW for 30 years} – \text{acceptable}$
    (Capacity and lifespan match with those suggested in Jung 2013)
  – Stable stage could be longer
    (If considering thermal conduction from surrounding rocks)
  – $110 \text{ million USD} \approx 10 \text{ (cents per kWh)} \times 5\text{MW} \times 25 \text{ years}$
  – Cost of drill, fracturing, build, operate, and maintenance?
Sensitivity Study of Some Design Constraints and Operational Parameters

Three comparative scenarios:

- Test 1 vs. 2: sensitivity to fracture horizontal spacing, $d_h$
- Test 1 vs. 3: sensitivity to well deviation angle, $\alpha$
- Test 3 vs. 4: sensitivity to flow rate per fracture, $q'_w$

<table>
<thead>
<tr>
<th>Test Case</th>
<th>Fracture horizontal spacing $d_h$ (m)</th>
<th>Well deviating angle $\alpha$</th>
<th>Mass flow rate per fracture $q'_w$ (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (base)</td>
<td>30</td>
<td>$0^\circ$</td>
<td>3.14</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>$0^\circ$</td>
<td>3.14</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>$45^\circ$</td>
<td>3.14</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>$45^\circ$</td>
<td>6.28</td>
</tr>
</tbody>
</table>
Test Case 2 ($d_h = 50\text{m}, \alpha = 0^\circ, q'_w = 3.14\text{kg/s}$)
sensitivity to fracture horizontal spacing, $d_h$

Evolution of $T_{\text{pro}}(^\circ\text{C})$ per fracture

Evolution of $Q_{\text{eff}}(\text{MW})$ per fracture
Sensitivity to $d_h$

$d_h = 30\text{m}$

vs.

$d_h = 50\text{m}$

Constants:

$\alpha = 0^\circ$

$q'_w = 3.14\text{kg/s}$

Results after up-scaling:

✔ 6 more years of stable stage

✔ $125\times10^6 \text{kWh}$ more in 30 years

?? Extra drilling
Test Case 3 ($d_h = 30m$, $\alpha = 45^\circ$, $q'_w = 3.14kg/s$) sensitivity to well deviation angle, $\alpha$

Evolution of $T_{pro}(^\circ C)$ per fracture

Evolution of $Q_{eff}(MW)$ per fracture
Sensitivity to $\alpha$

$\alpha = 0^\circ$ vs. $\alpha = 45^\circ$

Constants:

$d_h = 30m$
$q'_w = 3.14 kg/s$

Results after up-scaling:

✔ 0.2~0.6 MW more in 30 years

?? Feasibility of construction
Test Case 4 ($d_h = 30m$, $\alpha = 45^\circ$, $q'_w = 6.28$kg/s) sensitivity to flow rate per fracture, $q'_w$

Evolution of $T_{pro}(^\circ C)$ per fracture

Evolution of $Q_{eff}$(MW) per fracture
Sensitivity to $q'_w$

$q'_w = 3.14 \text{ kg/s}$ vs. $q'_w = 6.28 \text{ kg/s}$

Constants:
$\Delta h = 30 \text{ m}$  
$\alpha = 45^\circ$

Results after up-scaling:
✓ Doubled $Q_{\text{eff}}$ at early stage
✗ Only 7 years of stable stage
✗ Only 17
Conclusions and Future Work

• A conceptual EGS model
  – Parallel doublet wells connected by equidistant large single wing fractures
    ✓ Meets industrial production-scale
    ?? Geo-techniques to create the required fractures?
  – Dependence of heat production on some design constraints and parameters has been quantified
    • Fracture horizontal spacing
    • Well downward deviation
    • Flow rate
  – Future: include stimulation / fracturing into the model