Optimization of Experimental Parameters for Comparing Enhanced Geothermal Working Fluids in the Lab

Project Presentation
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Heat Flow Map of the United States (SMU Geothermal Lab), 2004
Outline:

- Motivation
- Goals
- System Model
- Cost Function
- Simplification Strategies
- Future Work
Motivation:

• America consumed 107 exajoules of energy in 2007 with 85% of that coming from fossil fuels. (EIA 2007)

• MIT estimated that the United States holds 13,000 zetajoules of energy in rock 3-10km deep (>100,000 times yearly demand)

Geothermal sources could provide “clean” power for millennia!!
Current Geothermal Limitations:

• Traditional Geothermal requires optimal geological conditions, and a source of water (very rare).
• Enhanced Geothermal Systems (EGS) attempts to create ideal conditions through methods such as fracturing and water injection.
• Obvious hot spots are near-fault zones but after the seismic event at 5 km below Basel (CH), this is too risky near a major metropolitan area.

Wanted: a safe and inexpensive source of heat.
Oh, small heat gradient; can we improve system efficiency?

**Super Critical Carbon Dioxide!**

Donald Brown, 2006 (LANL)

**Gas and Liquid Properties**

**The Idea:** Substitute supercritical CO$_2$ for H$_2$O as the heat transfer medium.

**Current Status:**

Quantitative assessment of the potential for operating EGS with supercritical CO$_2$ is at an early stage.

Studies to date suggest that supercritical CO$_2$ may have significant advantages over water.
Reference Case
TOUGH2 Simulation by Karsten Preuss (LBL)

\[ T_{\text{res}} = 200 \, ^\circ\text{C}, \quad P_{\text{res}} = 500 \text{ bar}, \quad T_{\text{inj}} = 20 \, ^\circ\text{C} \]

Theoretical advantages:

- strong buoyancy effects can provide safeguards against short-circuits
- more favorable wellbore hydraulics
- more benign rock-fluid interactions
- fluid losses can be beneficial . . .
CO₂ circulation fluid is de facto Carbon Sequestration!

- CO₂ mass flow of approximately **20 kg/s is required per MW** electric power capacity.
- From experience with long-term circulation tests with water-based systems, expect a **fluid loss rate of order 5%**, or 1 kg/s of CO₂ per MW electric power.
- For **1,000 MWe of installed EGS capacity**, the amount of fluid lost in circulation and stored underground is estimated as 1 tonne of CO₂ per second.
- This rate of fluid storage is equivalent to CO₂ emissions from **3,000 MWe of coal-fired power generation**.
Project Goals:

• Understand how the TOUGH2 Model works.
• Use techniques similar to those introduced in class to optimize a lab experiment that will measure the efficiency of SCCO2 vs H2O.

Experiment Optimization:

• Ensure a measurable difference in the two working fluids within a reasonable experimental run time, within laboratory constraints.
Experiment Setup

• Impose a fluid pressure differential across cylindrical porous media
• Apply heat flux to exterior of cylinder.

Want to know optimal parameters:
Initial fluid temp, imposed heat flux, initial media temp, ΔP, media permeability, media dimensions (L, R).
TOUGH2 - a general-purpose numerical simulation program for multi-phase fluid and heat flow in porous and fractured media.

Conservation equation for heat and mass:

\[
\frac{d}{dt} \int_V M dV_n = \int_{\Gamma} F \cdot n \, d\Gamma + \int_V q dV
\]

Where \( M \) is the mass/heat accumulation term, \( F \) is the flux term, \( n \) is a vector normal to the surface \( \Gamma \) pointing inwards, \( q \) is a heat/mass sink or source term.
Ignoring dispersion and diffusion, the fluid mass flux is given by Darcy’s law:

\[
\frac{d}{dt} \int_V \phi \rho_F dV_n = \int_\Gamma -\frac{k \rho_F}{\mu} (\nabla P - \rho_F g) \cdot n \, d\Gamma + \int_V q \, dV
\]

Including conductive and convective flux, the heat balance equation is:

\[
\frac{d}{dt} \int_V (1 - \phi) \rho_R C_R T + \phi \rho_F u_F dV_n = -\int_\Gamma -\lambda \nabla T + h \mathbf{F}_F \cdot n \, d\Gamma + \int_V q_h \, dV
\]

Equations coupled by fluid mass flux, fluid mass accumulation and fluid properties.
Cost Function

• Efficiency can be defined as the ratio of the work input into the system to the heat extracted from the system.

• The goal is to maximize the cost function $J$ over a finite time period:

$$\max J = \max \left( \int_T \frac{-d}{dt} \int_V \frac{M_h dV}{P q_{in}} dt \right)$$
Problem Formulation:

\[
\max J = \max \left( \int_T -\left( \int_{\Gamma} -\lambda \nabla T + h \left( \int_A \frac{k \rho_F}{\mu} \frac{d}{dz} (P + \rho g) dA \right) \cdot n \, d\Gamma + \int_V q_h \, dV \right) dt \right)
\]

st:

\[
\frac{d}{dt} \int_V \phi \rho_F dV_n = \int_{\Gamma} -\frac{k \rho_F}{\mu} (\nabla P - \rho_F g) \cdot n \, d\Gamma + \int_V q \, dV
\]

Mass balance

\[
\frac{d}{dt} \int_V (1 - \phi) \rho_R C_R T + \phi \rho_F u_F dV_n = -\int_{\Gamma} -\lambda \nabla T + hF_F \cdot n \, d\Gamma + \int_V q_h \, dV
\]

Heat balance

\[\mu(T), \rho(T, P) \text{ are properties of the fluid}\]
\[\text{Pinlet} \ \text{pressure at the point of fluid injection}\]
\[\text{Pout} \ \text{pressure at the exit of the core}\]
\[T_0 \ \text{initial temperature of the core}\]
\[h_{inlet} \ \text{specific enthalpy of injected fluid}\]
\[q_h \ \text{heat input into the system if any}\]
\[\kappa \ \text{permeability of the core}\]
\[\Gamma(L, R), V(L, R) \ \text{functions of core length and radius}\]
Simplifications:
Parallel Plate Porous Media Flow

- Constant $\rho$
- Steady state
- Low-permeability
- Uniform heat flux from plates
- Negligible flow in $y$ direction
- High Péclet number
  (negligible diffusion, and axial conduction)

A. Narasimhan and J Lage 2001

Jean Claude Eugène Péclet
Simplified Model

A. Narasimhan and J Lage 2005

Variable Viscosity Forced Convection in Porous Medium Channels

- Originally for study of military avionics cooling.
- Using simplifications and starting with Navier Stokes Equations:

\[
C_0 \rho K_0 u^2 + \mu(T)u - GK_0 = 0 \quad G = -\frac{\partial p}{\partial x}
\]

\[
\frac{\partial^2 T}{\partial y^2} = \frac{\rho c_p}{k_e} u \frac{\partial T}{\partial x}
\]

- Use algebra, thermodynamics, and Perturbation Analysis to create an approximate solution.
1\textsuperscript{st} Perturbation Approximation

Zero Order Solution (fixed viscosity): \[ G = \frac{\mu_r}{K_0} U_0 + C_0 \rho U_0^2 \]

Dependence on variable viscosity: \[ u = F(\mu(T)) \]

2\textsuperscript{nd} Order Taylor Expansion:
\[
F(\mu(T)) = F(\mu_r) + F'(\mu_r)\mu'_r(T - T_r) + \frac{1}{2} \left[ F''(\mu_r)\mu''_r + F'''(\mu_r)\mu'_r^2 \right] (T - T_r)^2
\]
\[ \mu(T_r) = \mu_r \]

First order approximate solution:
\[ u_1 = a_1 + \frac{a_2 N}{2} \left[ 1 - \left( \frac{y}{H} \right)^2 \right] \]
\[
a_1 = \frac{GK_0}{2\mu_w} \left[ -1 + \sqrt{1 + 4\xi} \right], \quad a_2 = \frac{GK_0}{2\mu_w \xi} \left[ 1 - \frac{1}{\sqrt{1 + 4\xi}} \right]
\]
\[ N = \frac{q''H}{k_e} \frac{1}{\mu_w} \left( \frac{d\mu}{dT} \right)_{T_w} \]
Approximate Solution Results:

From A. Narasimhan and J Lage 2005

Approx. Soln. Only Gives Profiles in terms y. Dependence on x (axial) is only due to Wall Temp.
Future work...

By the end of the semester:

• Verify that simplified model assumptions make sense for lab setup (CO2 probably OK, H2O??)
• State cost function in terms of new model, attempt to optimize.
• Finish estimate of controllable parameter limits, (equipment catalogs, space constraints, etc.)
Summer and beyond...

- Rederive with cylindrical geometry
- Create program or tables for SCCO2 properties as a function of temperature and pressure (as well as differentials)
- Integrate variable density.
- Confirm results with TOUGH2
- Build Apparatus!

Important Summer Work!!
Questions - References


• Karsten Pruess, Enhanced geothermal systems (EGS) using CO2 as working fluid--A novel approach for generating renewable energy with simultaneous sequestration of carbon, Geothermics Volume 35, Issue 4, , August 2006, Pages 351-367

