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

Project Presentation

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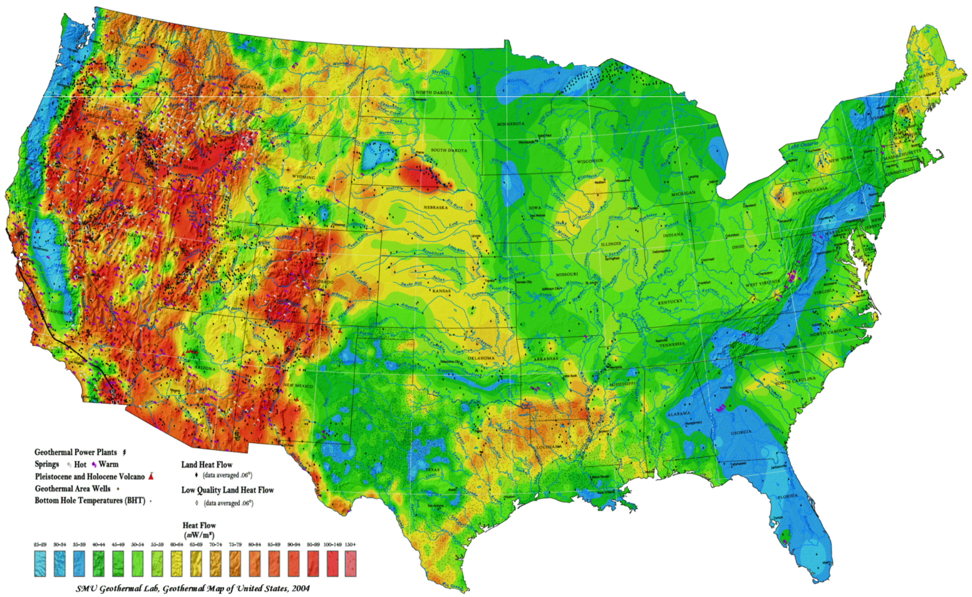
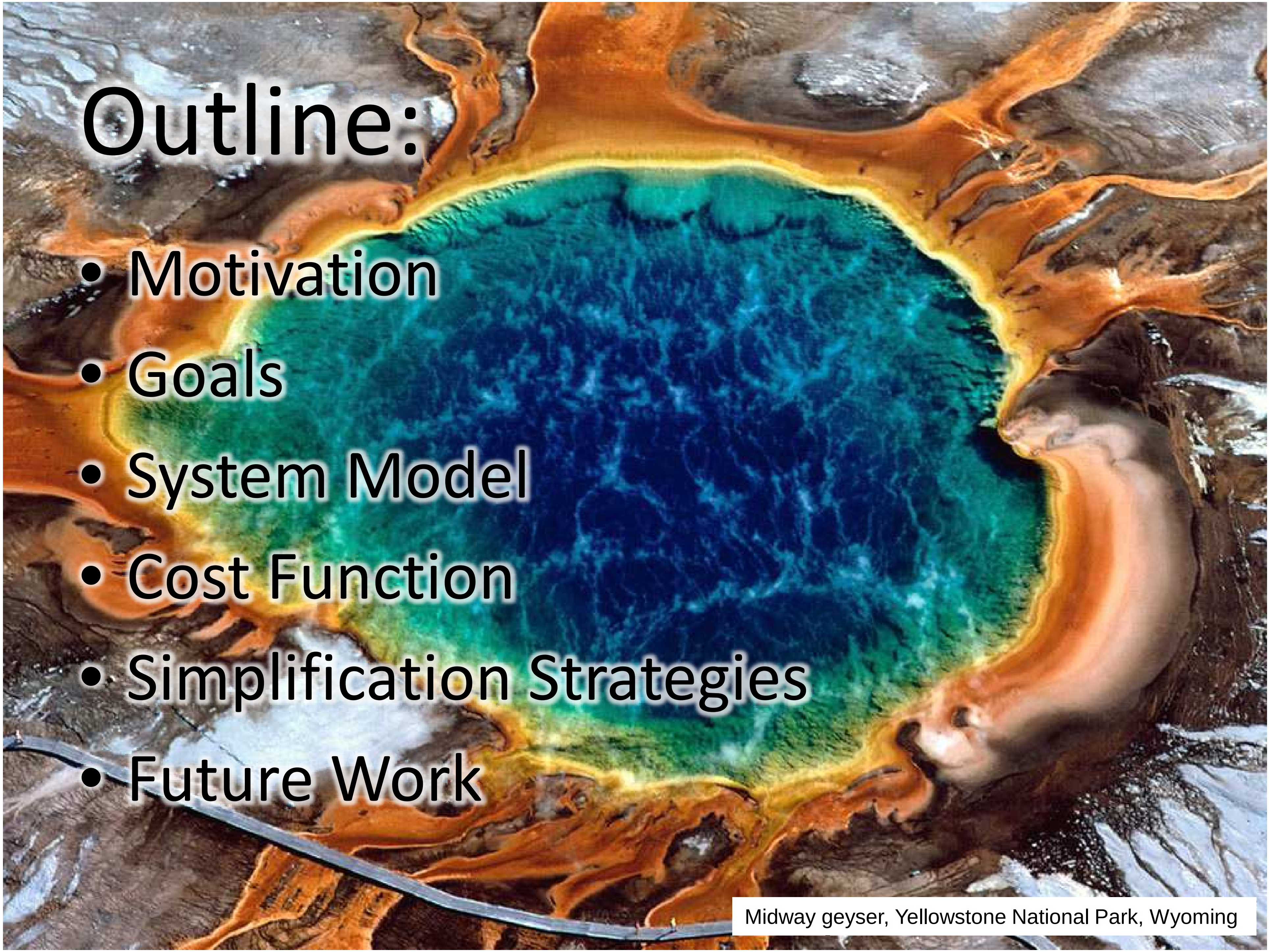
CE 291F Spring 2009



Heat Flow Map of the United States (SMU Geothermal Lab), 2004

Outline:

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



Midway geyser, Yellowstone National Park, Wyoming

Motivation:

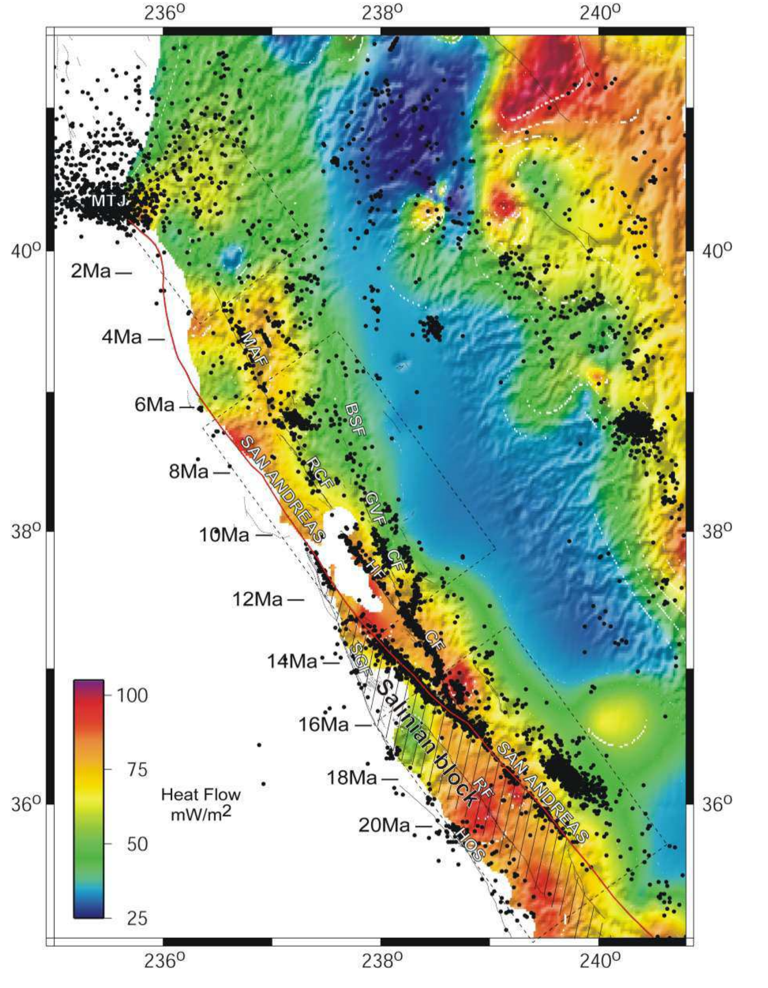
- America consumed 107 exajoules of energy in 2007 with 85% of that coming from fossil fuels. (EIA 2007)
- MIT estimated that the United States holds 13,000 zetajoules of energy in rock 3-10km deep (>100,000 times yearly demand)

Coal fired plant (VA).

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.

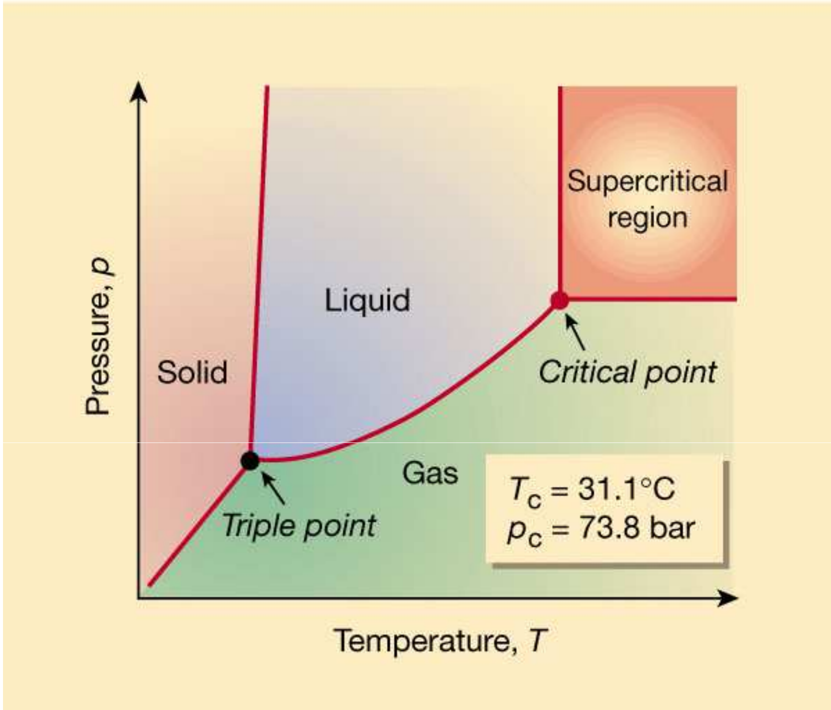


Wanted: a safe and inexpensive source of heat.

Oh, small heat gradient; can we improve system efficiency?

Super Critical Carbon Dioxide!

Donald Brown, 2006 (LANL)



<u>Gas and Liquid Properties</u>

The Idea: Substitute super critical CO_2 for H_2O as the heat transfer medium.

<u>Current Status</u>:

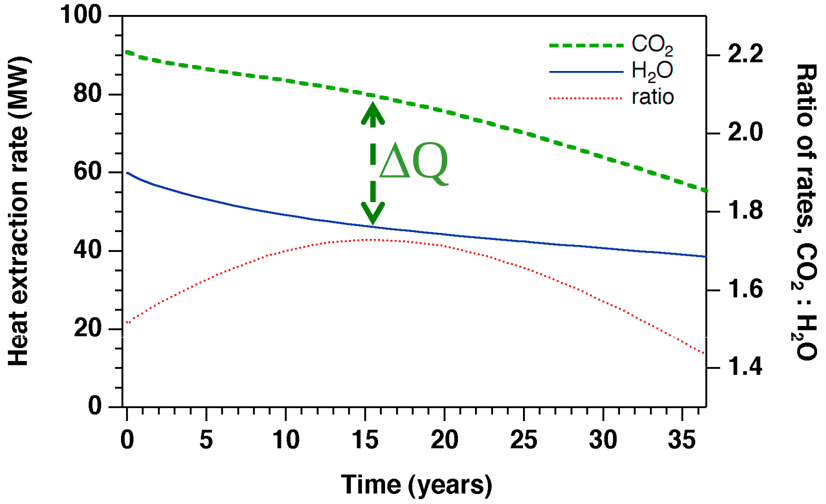
Quantitative assessment of the potential for operating EGS with supercritical CO_2 is at an early stage.

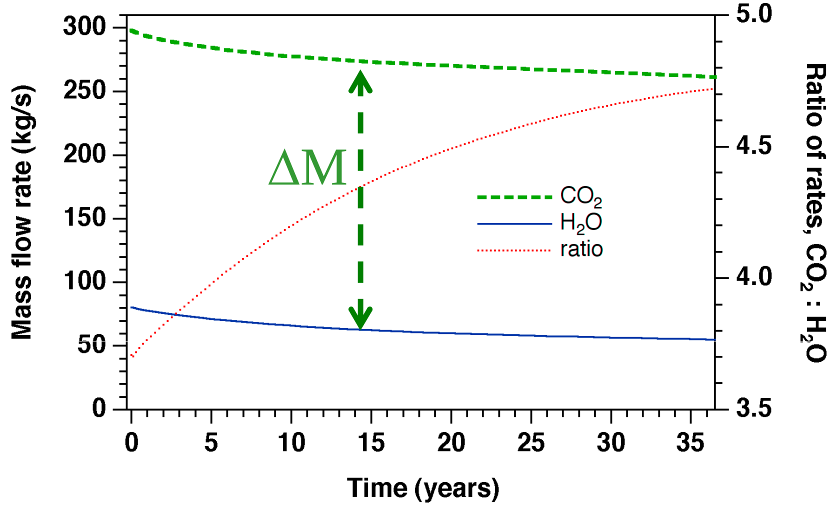
Studies to date suggest that supercritical CO_2 may have significant advantages over water.

Reference Case

TOUGH2 Simulation by Karsten Preuss (LBL)

T_{res} = 200 ˚C, P_{res} = 500 bar, T_{inj} = 20 ˚C





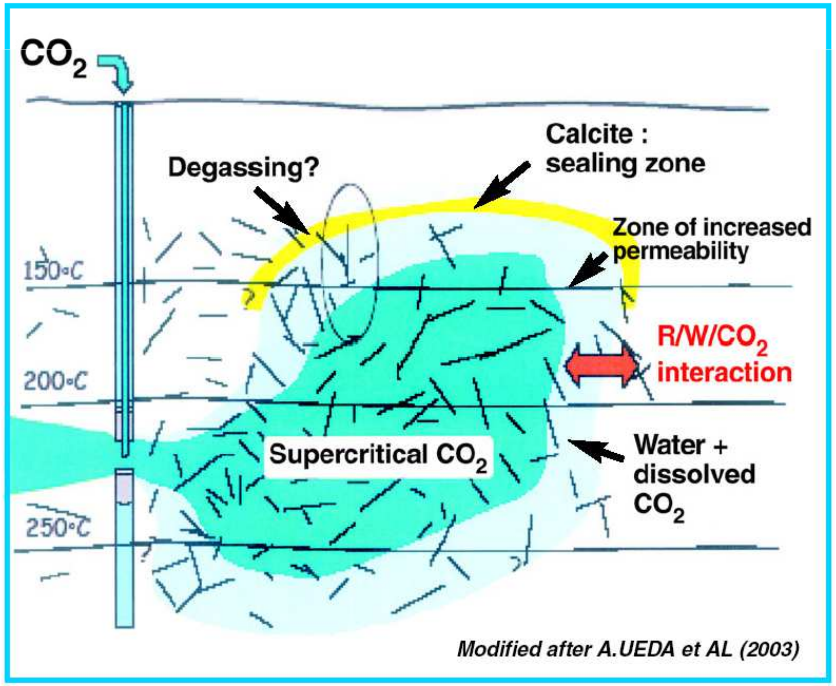
From: Karsten Pruess, LBL Berkeley

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 . . .

CO_2 circulation fluid is de facto Carbon Sequestration!

- CO_2 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 CO_2 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 CO_2 per second.
- This rate of fluid storage is equivalent to CO_2 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:

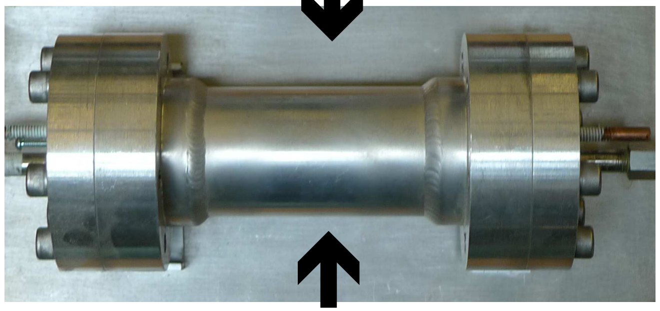
- Ensure a measurable difference in the two working fluids within a reasonable experimental run time, within laboratory constraints.

Experiment Setup

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

Heat in

Fluid in



Fluid out

Heat in

Want to know optimal parameters:

Initial fluid temp, imposed heat flux, initial media temp, ΔP, media permeability, media dimensions (L, R).

System Model - TOUGH2

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:

$$\frac{d}{dt}\int_V M\,dV_n = \int_\Gamma \mathbf{F} \bullet \mathbf{n}\,d\Gamma + \int_V q\,dV$$

Where *M* is the mass/heat accumulation term, **F** is the flux term, **n** is a vector normal to the surface Γ pointing inwards, *q* is a heat/mass sink or source term.

System Model - TOUGH2

Ignoring dispersion and diffusion, the fluid mass flux is given by Darcy's law:

$$\frac{d}{dt}\int_V \phi\rho_F dV_n = \int_\Gamma -\frac{\mathbf{k}\rho_\mathbf{F}}{\mu}\left(\nabla\mathbf{P} - \rho_\mathbf{F}\mathbf{g}\right)\bullet\mathbf{n}\, d\Gamma + \int_V q dV$$

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

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

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:

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

Problem Formulation:

$$\max J = \max \left(\int_T \frac{-\left(\int_\Gamma -\lambda \nabla \mathbf{T} + \mathbf{h} \left(\int_\mathbf{A} \frac{\mathbf{k}\rho_\mathbf{F}}{\mu} \frac{\mathbf{d}}{\mathbf{dz}} \left(\mathbf{P} + \rho \mathbf{g} \right) \mathbf{dA} \right) \bullet \mathbf{n} \, d\Gamma + \int_V q_h dV \right)}{P_{inlet} \int_{A_{inlet}} \frac{k\rho_F}{\mu} \frac{d}{dz} \left(P + \rho g \right) dA_{inlet}} dt \right)$$

st:

$$\frac{d}{dt} \int_V \phi \rho_F dV_n = \int_\Gamma - \frac{\mathbf{k}\rho_\mathbf{F}}{\mu} \left(\nabla \mathbf{P} - \rho_\mathbf{F} \mathbf{g} \right) \bullet \mathbf{n} \, d\Gamma + \int_V q dV$$

Mass balance

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

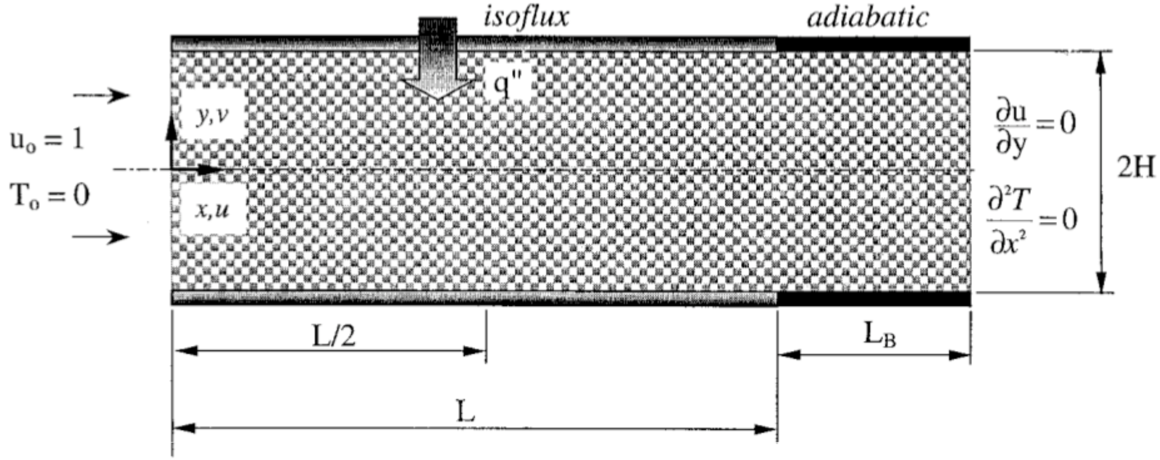
Heat balance

$\mu(T), \rho(T, P)$ are properties of the fluid

P_{inlet} pressure at the point of fluid injection
P_{out} pressure at the exit of the core
T_0 initial temperature of the core
h_{inlet} specific enthalpy of injected fluid
q_h heat input into the system if any
κ permeability of the core
$\Gamma(L, R), V(L, R)$ functions of core length and radius

Controllable ICs & BCs

Simplifications: Parallel Plate Porous Media Flow



A. Narasimhan and J Lage 2001

- Constant ρ
- steady state
- low-permeability,
- Uniform heat flux from plates
- Negligible flow in y direction
- High Péclet number
  (negligible diffusion, and axial conduction)

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:

$$C_0 \rho K_0 u^2 + \mu(T) u - G K_0 = 0 \qquad G = -\frac{\partial p}{\partial x}$$

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

- Use algebra, thermodynamics, and Perturbation Analysis to create an approximate solution.

1st 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: $u = F(\mu(T))$

2nd 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:

$$u_1 = a_1 + \frac{a_2 N}{2}\left[1 - \left(\frac{y}{H}\right)^2\right]$$

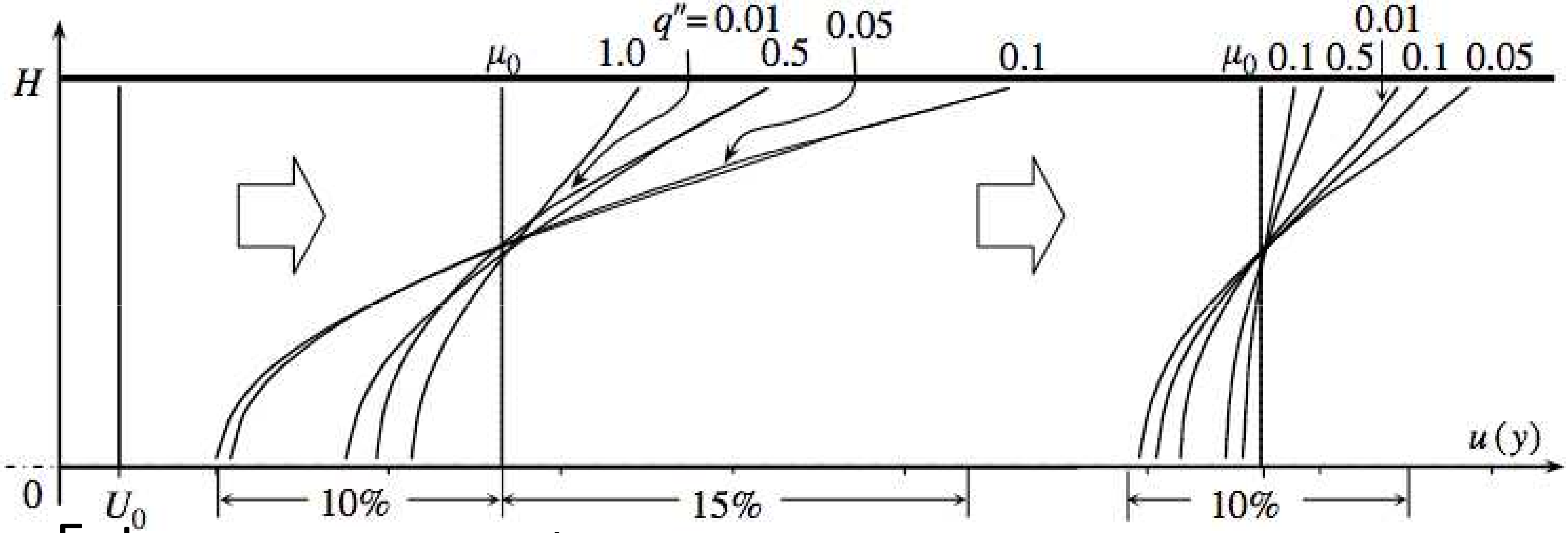
No Dependence on x?
High Péclet assumption.

$$a_1 = \frac{GK_0}{2\mu_w}\left[\frac{-1 + \sqrt{1 + 4\zeta}}{\zeta}\right], \qquad a_2 = \frac{GK_0}{2\mu_w \zeta}\left[1 - \frac{1}{\sqrt{1 + 4\zeta}}\right]$$

$$N = \frac{q'' H}{k_e} \frac{1}{\mu_w} \left(\frac{d\mu}{dT}\right)_{T_w}$$

Approximate Solution Results:

From A. Narasimhan and J Lage 2005



Entrance Slug Flow

x=L/2

x=L

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

Future work…

Me at a geyser, Wyoming 2008

By the end of the semester:

- Verify that simplified model assumptions make sense for lab setup ($CO2$ probably OK, $H20$??)
- 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

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