Geothermal Energy Utilization via Effective Design of Ground-Coupled Heat Exchange System

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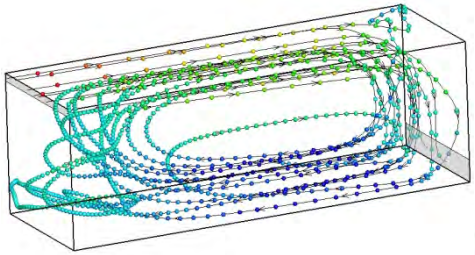
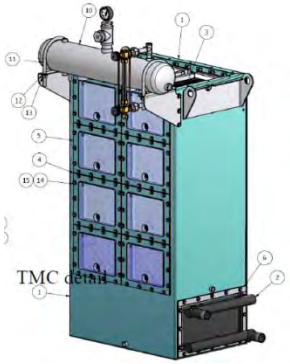
05/18/2010

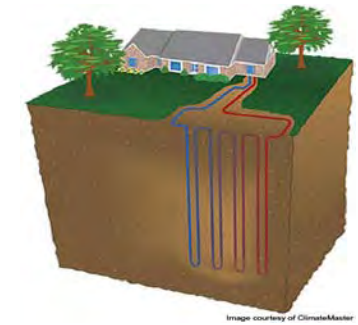
Geothermal energy is the most recent research subject AJ and I have worked on together at UT

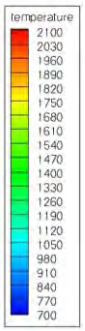
Current Research Activities

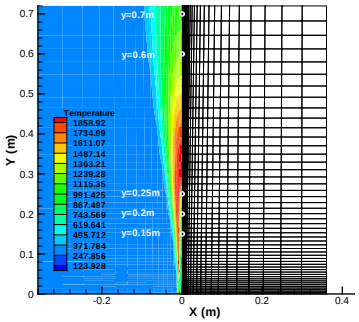
- **Energy Efficiency**
  - Building Energy Efficiency (Data Center Thermal Management and Air Flow)
  - Waste Heat Recovery in Industrial Processes
  - Reactive Flow Film Cooling in Turbine
- **Renewable Energy**
  - Geothermal Energy Heat Exchange System
  - Bio/Alternative Fuel Combustion & Compatibility
- **Computational Fluid Dynamics Applications**

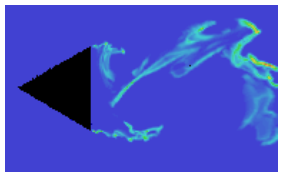










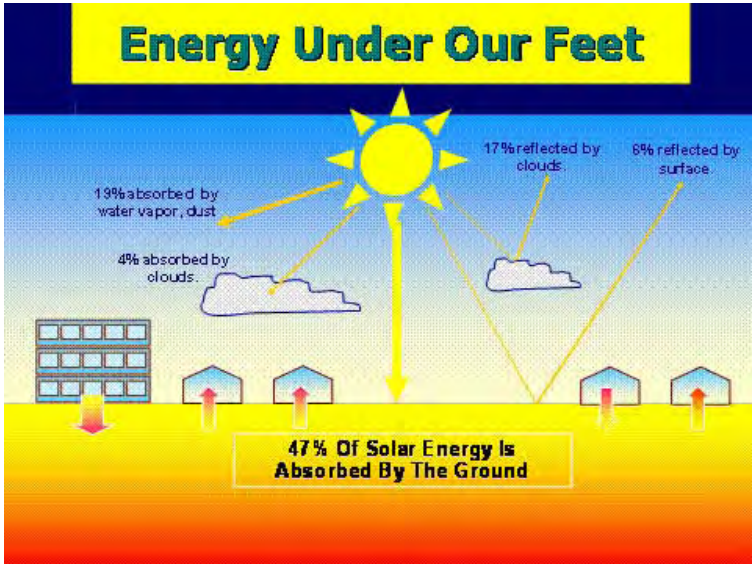


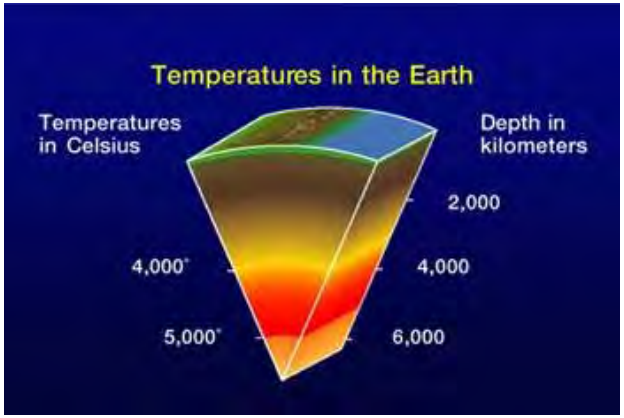
Outline of Presentation

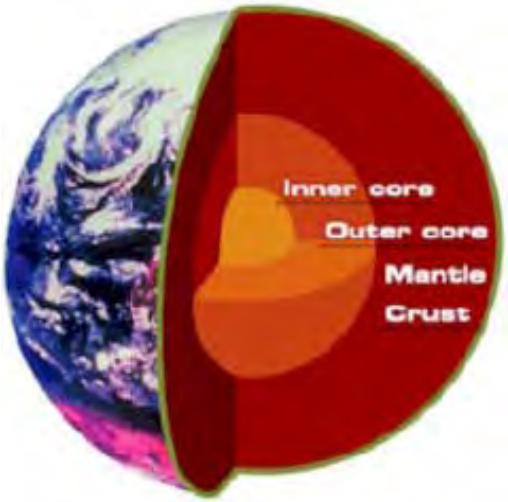
- **Introduction to Geothermal Energy**
- **Overview of Existing Research in Geothermal Heat Pump**
  - Geothermal heat pump basics
  - Previous research
- **Geothermal Heat Exchange System R&D**
  - Issues and challenges
  - Effective computational algorithm development
  - Selected results and discussion
- **Closing Remarks**

What is Geothermal Energy?

- **Geothermal energy is heat (thermal) derived from the earth (geo): soil, fluid, rock, and magma**
  - Clean
  - Renewable
  - Reliable (average system availability of 95%)
  - Homegrown



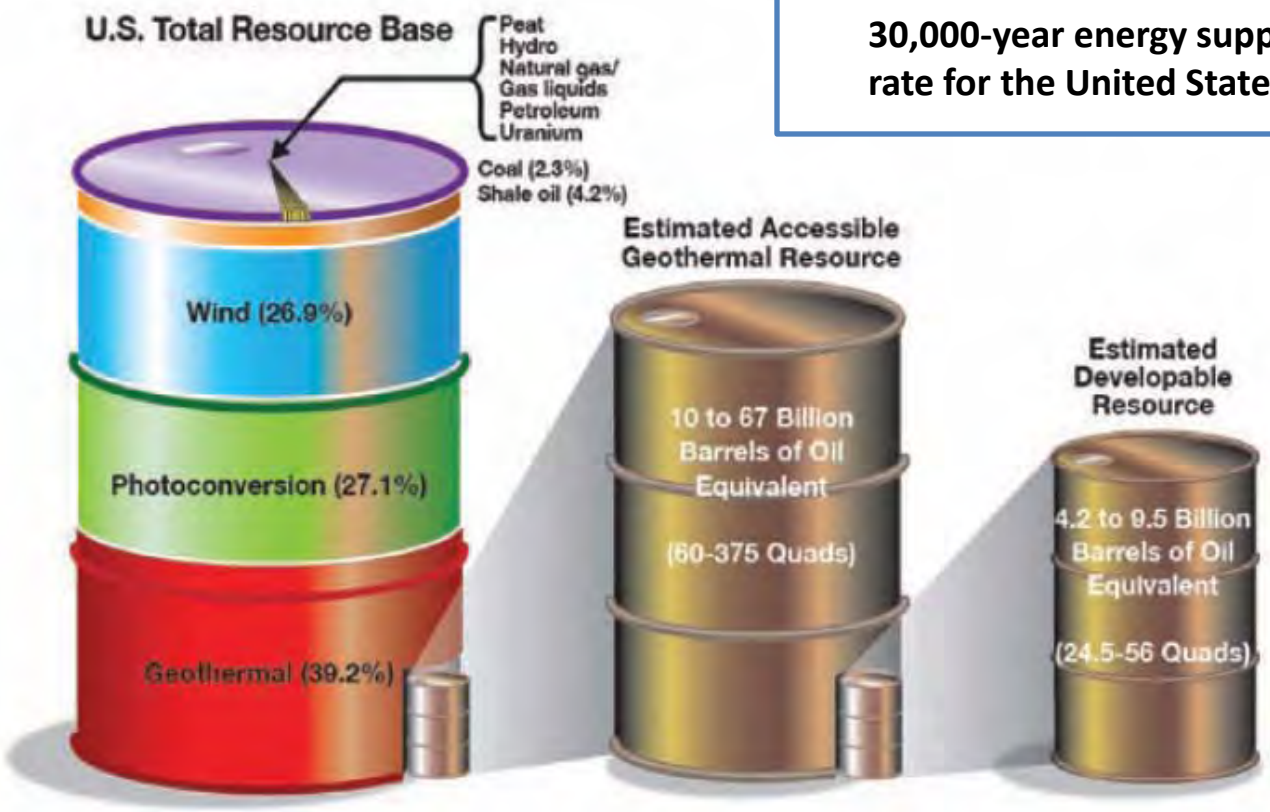




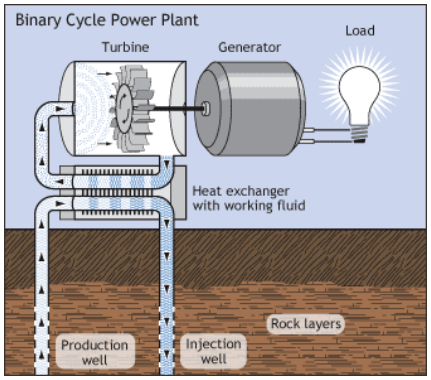
U.S. Geothermal Resources

U.S. Energy and Geothermal Resources (NREL)

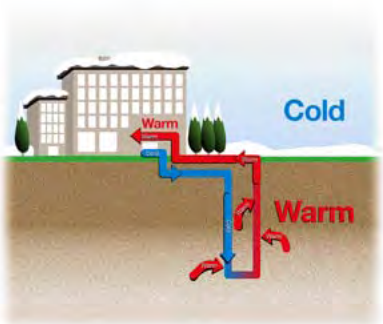
Domestic resources are **equivalent to a 30,000-year energy supply at our current rate for the United States!**

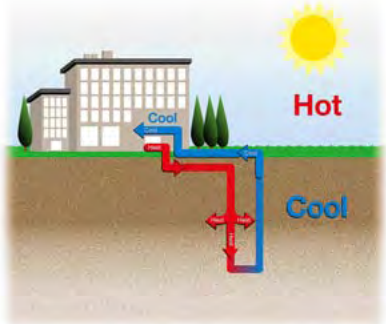


Geothermal Utilization

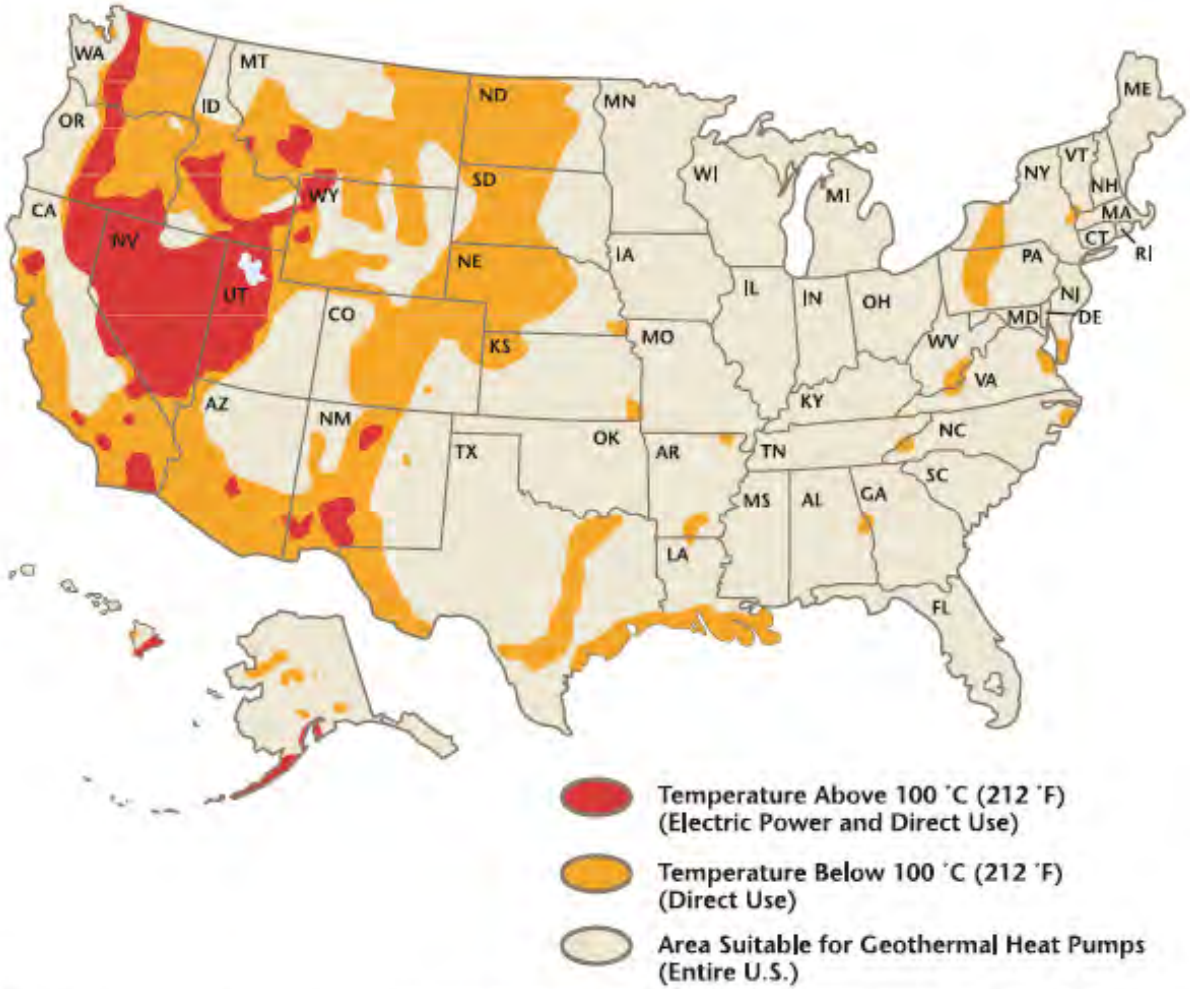


- **Power Plants (Hydrothermal Systems and Enhanced Geothermal Systems)**
  - Dry steam plants
  - Flash steam plants
  - Binary-cycle plants
- **Direct Use**
  - Greenhouse warming
  - Ice melting on roads
  - District heating systems
  - Various industrial processes
- **Geothermal Heat Pumps**
  - Heating in winter
  - Cooling in summer





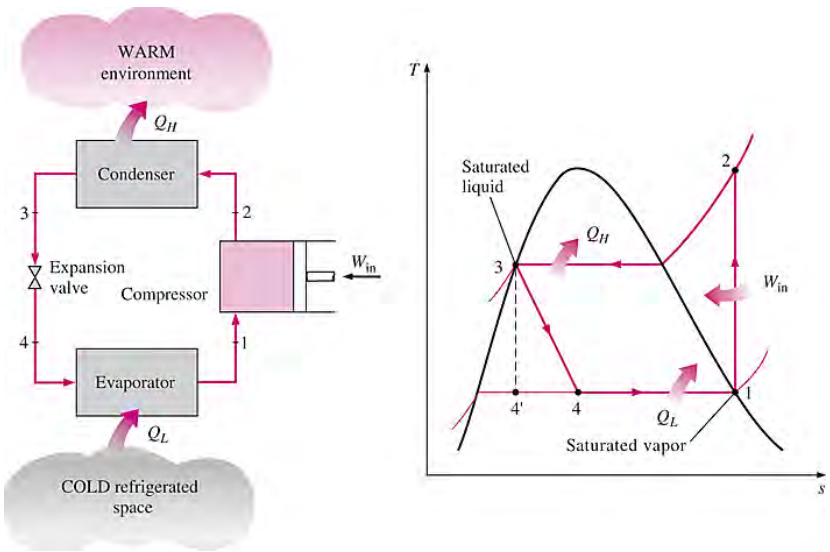
Geothermal Utilization Map (NREL)



The Nation's geothermal resources represent a huge and viable energy resource, providing the U.S. with various ways to use them and enhance national security, and economic and environmental health.

Thermodynamic Cycle for a Heat Pump

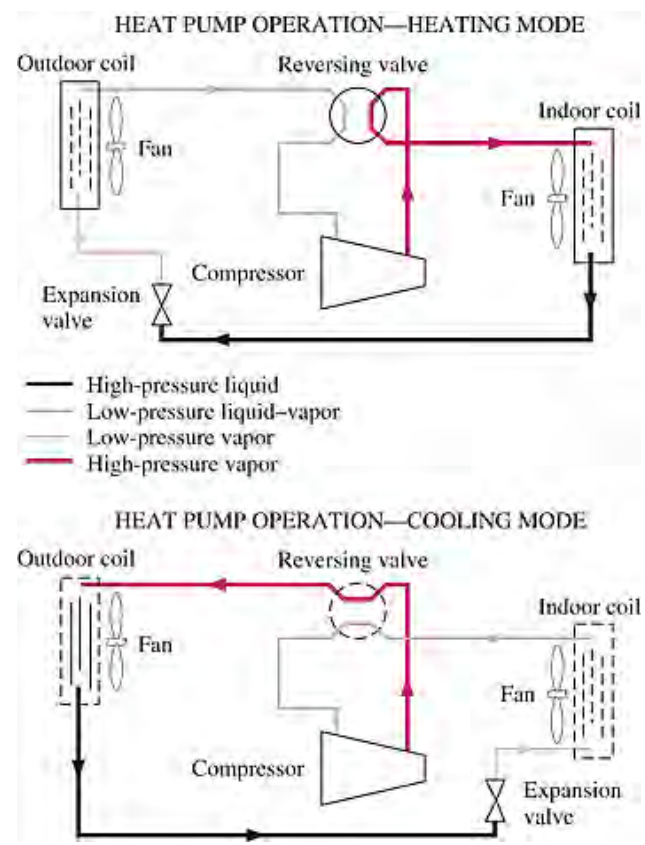
Ideal Vapor-Compression Cycle



Key Components

- Condenser
- Evaporator
- Expansion valve
- Compressor

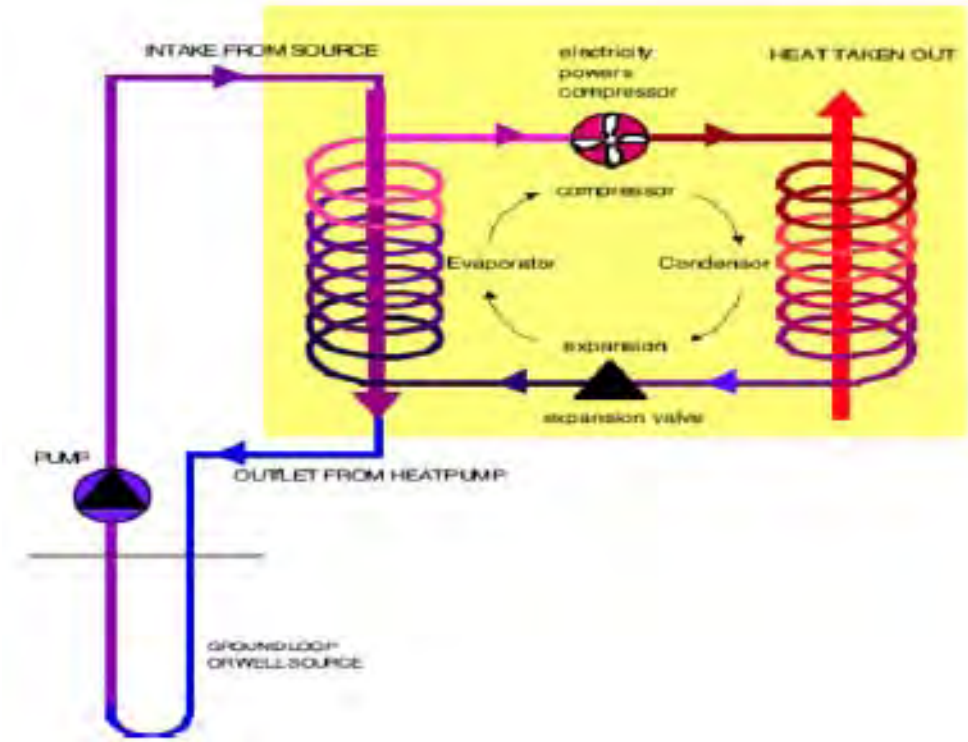
Heat Pump Operation Modes



(Cengel & Boles, 2008)

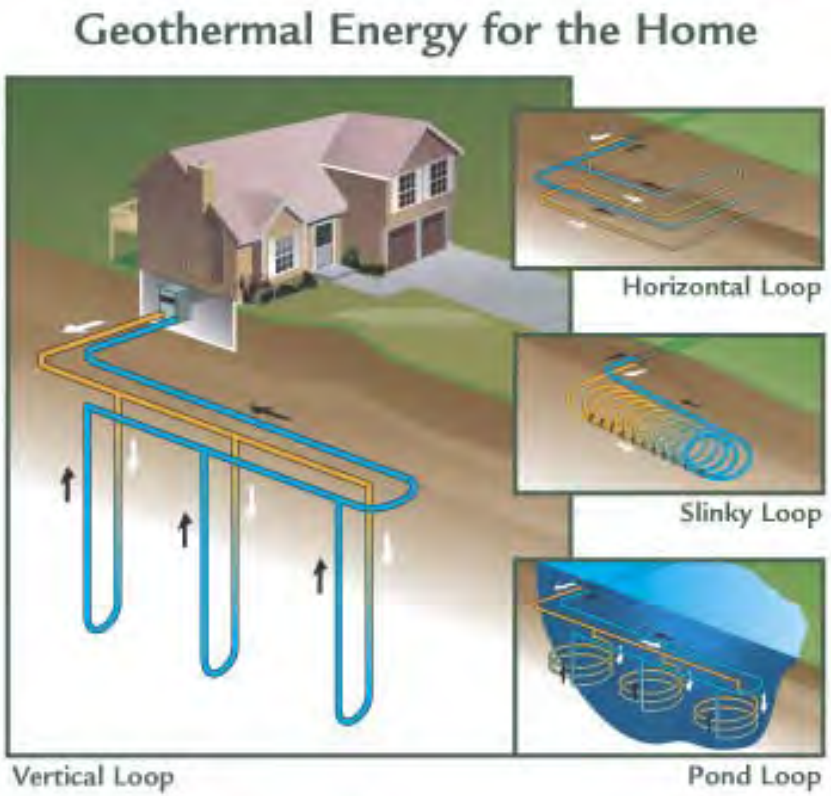
Geothermal Heat Pump

How Does a Geothermal Heat Pump work?



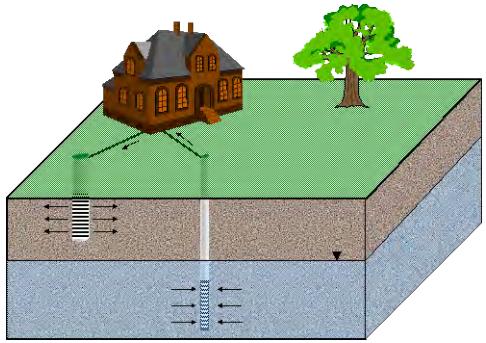
Earth Connections

Typical Closed Loops

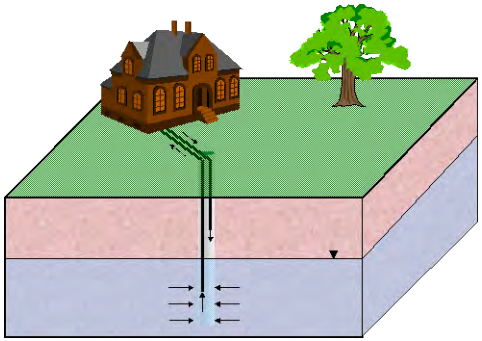


Typical Open Loops

- Groundwater

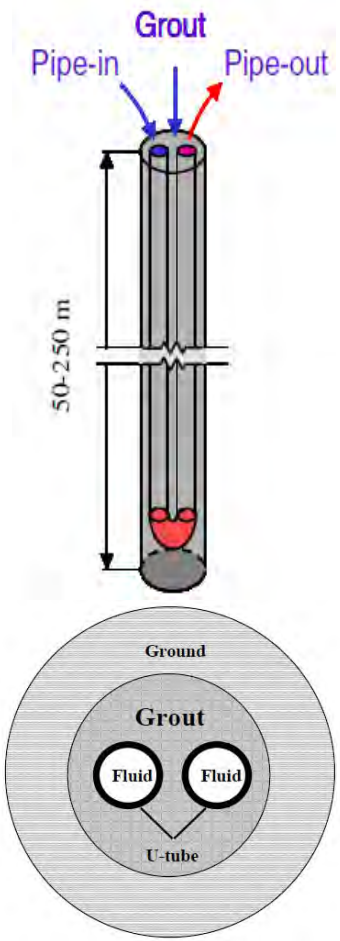


- Standing column well

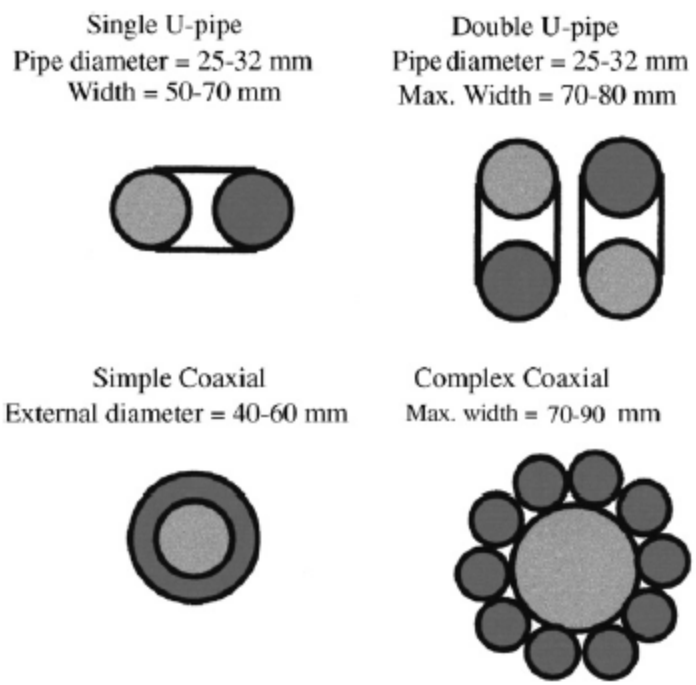


Typical Vertical Geothermal Heat Exchangers

U-Tubes



Others

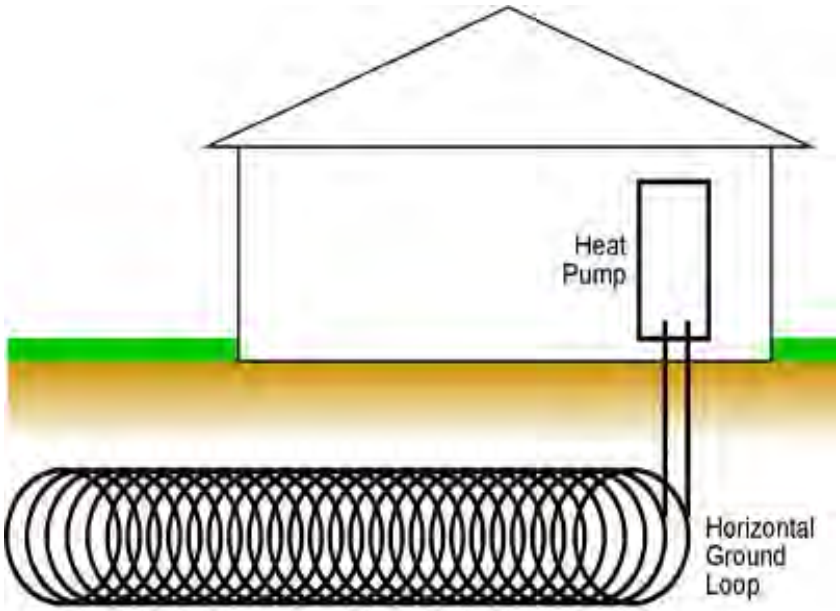


(Florides & Kalogirou, 2007)

More on Geothermal Heat Pump

- **EPA on GHP (1993)**
  - GeoExchange (GHP) systems are the most energy efficient, environmentally clean, and cost-effective space conditioning systems available (source: "Space Conditioning: The Next Frontier," EPA 430-R-93-004, April 1993)
- **DOE/ORNL on GHP (2008)**
  - If the federal government set a goal for the U.S. buildings sector to use no more nonrenewable primary energy in 2030 than it did in 2008, based on previous analyses (updated and summarized in this report), it is estimated that 35 to 40 percent of this goal, or a savings of 3.4 to 3.9 quads annually, could be achieved through aggressive deployment of GHPs.
- **U.S. Adoption of GHP**
  - U.S. was once world leader (> 600,000 units in 2005)
  - Europe ranked higher on per capita basis (now absorbing 2 to 3 times the number of GHP units annually as do the U.S.)
  - Market growth rates in Europe, parts of Asia (China, South Korea), and Canada exceed those in the United States.
- **Key Obstacles**
  - Upfront installation cost
  - Public awareness
- **Major Needs in R&D**
  - Low cost, efficient components/system
  - Advanced design tools for component/system
  - Long term performance/sustainability

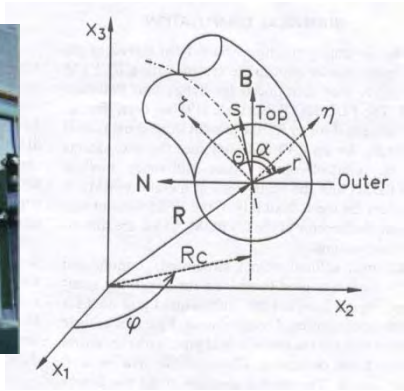
Helical Pipe Heat Exchanger in GHP

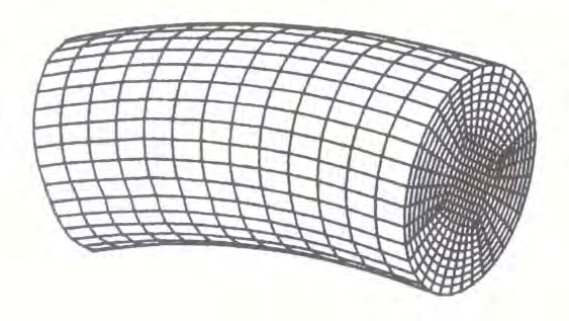


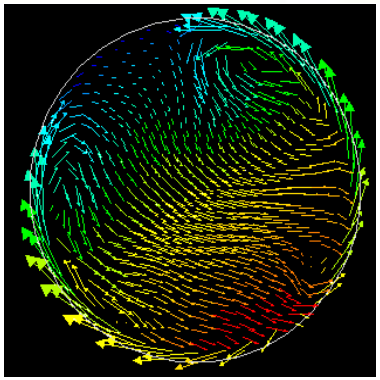
Surface Water Heat Pump Systems (OSU)

My Group's Previous Work in Helical Pipe Heat Exchanger

- Applications
  - Heat exchangers, evaporators and condensers, piping systems
- Research subjects
  - 3D developing turbulent flows
  - Heat transfer in near-critical region
  - Combined convection-radiation
  - Axial/secondary flow laser visualization
  - Condensation heat transfer
- **Publications (1996-2007 by C.X. Lin et al.)**
  - **Journal papers: 12**
  - **Conference papers: 18**

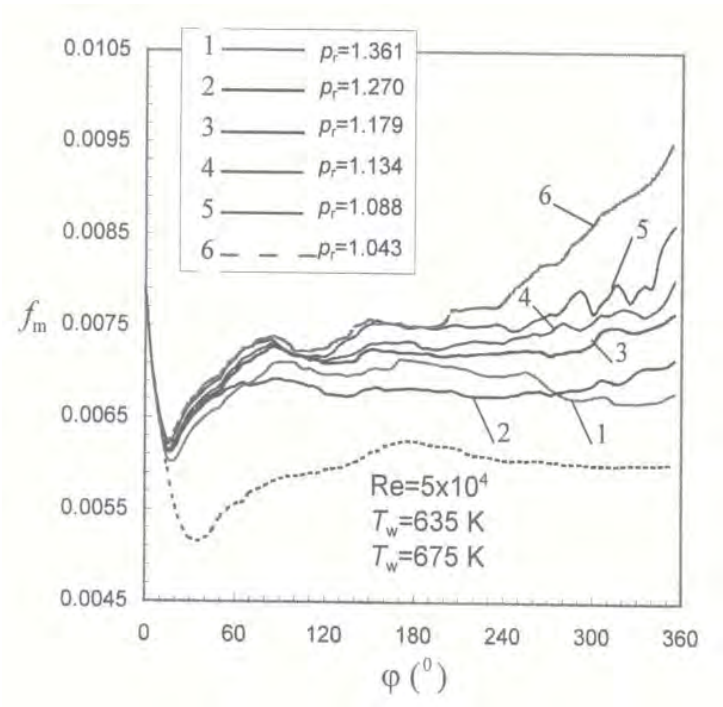


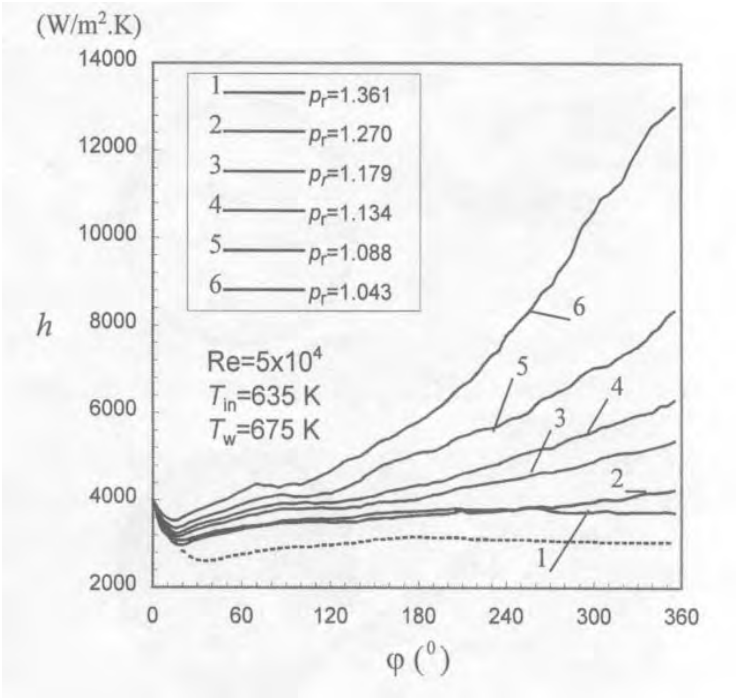




Turbulent Flow and Heat Transfer in Helical Pipes

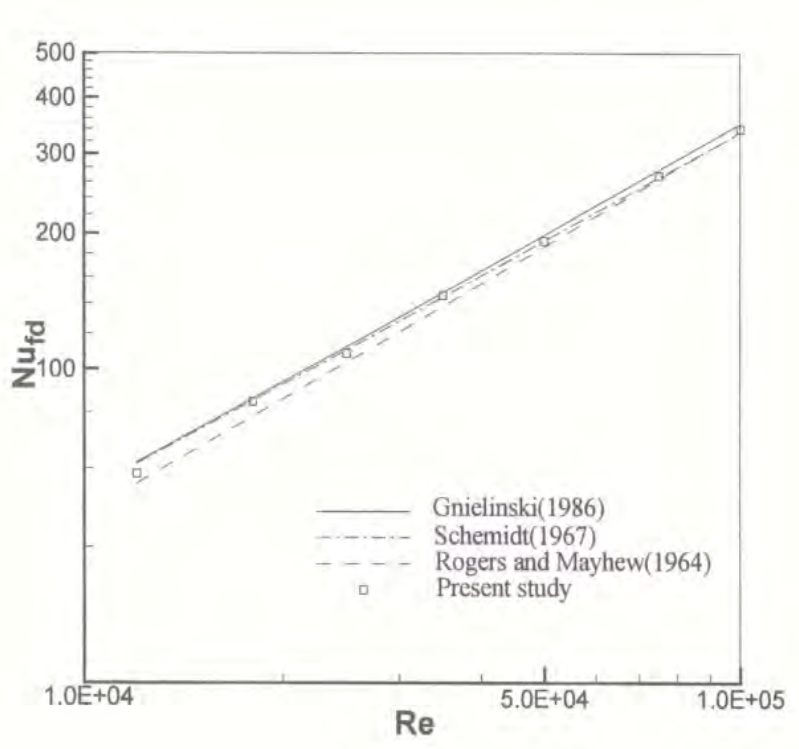
- Turbulent Heat Transfer near Critical Point





Turbulent Flow and Heat Transfer in Helical Pipes

- Fully Developed Turbulent Heat Transfer



$$Nu_{fd} = \frac{(f/8)\, Re \cdot Pr}{1 + 12.7\sqrt{f/8}(Pr^{2/3} - 1)} \left(\frac{Pr}{Pr_w}\right)^{0.14}$$

$$f = [0.3164/Re^{0.25} + 0.03\delta^{0.5}]\left(\frac{\mu_w}{\mu}\right)^{0.27}.$$

$$\frac{Nu_{fd}}{Nu_s} = 1.0 + 3.6(1 - \delta)\delta^{0.8}$$

$$Nu_s = 0.023 Re^{0.8} \cdot Pr^{0.4}.$$

The State-of-the-Art in Geothermal Vertical Heat Exchanger

- **Analytical Methods**
  - Line heat source theory (Ingersol and Plas, 1948)
  - Cylindrical heat source theory (Ingersoll et al, 1954)
  - ***Observation: simple, but too simplified***
- **Semi-Analytical Methods**
  - Analytical method combined with numerical method (Eskilson and Claeson, 1988)
  - ***Observation: still simple, but too simplified***
- **Numerical Methods – Heat Conduction Simulation**
  - 2D heat conduction (Muraya et al 1996; Yavuzturk et al 1999)
  - Quasi-3D heat conduction with 1D fluid aveage temperature (Al-Khoury et al 2005; Lee and Lam 2008)
  - ***Observation: more details, but not enough fluid flow effects***
- **Numerical methods – Computational Fluid Dynamics (CFD)**
  - 3D fluid flow and coupled heat transfer (Ma et al 2006)
  - ***Observation: high fidelity, but too expensive (millions of cells required)***

Full 3D Governing Equations

-Reynolds-Averaged Navier-Stokes (RANS) Equations

Continuity

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=S_m$$

Momentum

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}(\rho u_i u_j)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right]+\frac{\partial}{\partial x_j}(-\overline{\rho u_i' u_j'})+\rho g_i$$

Energy

$$\frac{\partial}{\partial t}(\rho E)+\frac{\partial}{\partial x_i}[u_i(\rho E+p)]=\frac{\partial}{\partial x_j}\left[\left(\mathrm{k}+\frac{C_p\mu_t}{\mathrm{Pr}_t}\right)\frac{\partial T}{\partial x_j}+u_i(\tau_{ij})_{eff}\right]+S_h$$

Turbulence Low-Re Model

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho u_i k)=\frac{\partial}{\partial x_i}\left[(\mu+\mu_t/\sigma_k)\frac{\partial k}{\partial x_i}\right]-\rho\varepsilon$$
$$+\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j}-2\mu\left(\frac{\partial k^{1/2}}{\partial x_j}\right)^2$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho u_i\varepsilon)=\frac{\partial}{\partial x_i}\left[(\mu+\mu_t/\sigma_\varepsilon)\frac{\partial \varepsilon}{\partial x_i})\right]+f_1C_1\frac{\varepsilon}{k}\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j}$$
$$-f_2C_2\rho\frac{\varepsilon^2}{k}+2\mu\mu_t\left(\frac{\partial^2 u_i}{\partial x_j\partial x_m}\right)^2/\rho$$

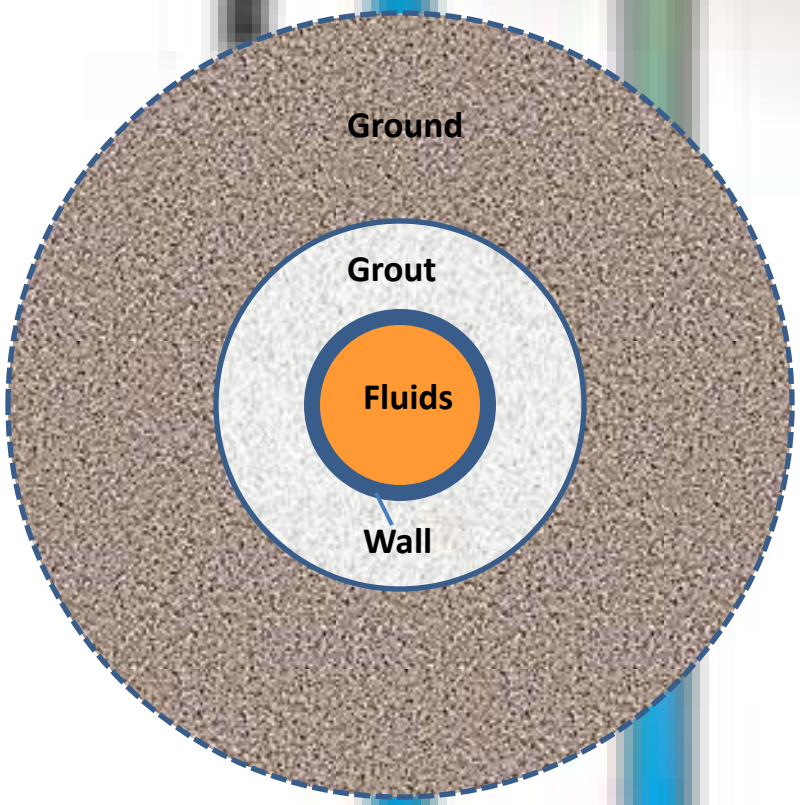
Fluid

Conduction

$$\rho C_p\frac{\partial T}{\partial t}=\frac{\partial}{\partial x_i}(\mathrm{k_i}\frac{\partial T}{\partial x})$$

Solid

The Multiphysics Challenges

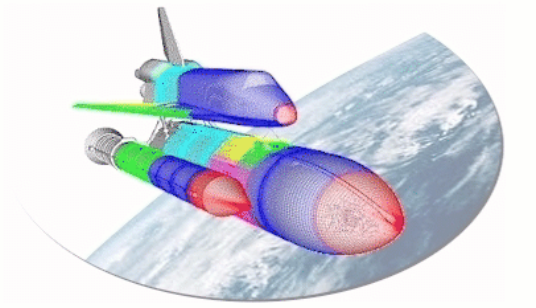


- **Huge Scale Disparity**
  - L/D ~ 10^4
- **Coupled heat transfer**
  - Multidomain interactions
    - Fluid-solid coupling
    - Solid-solid coupling (conduit wall, grout, formation)
- **Three-dimensional**
- **Turbulent flow**
- **Sharp U-Turn**

UT CFD Lab-Hardin Geotech Collaboration

- **Develop and validate a computational algorithm for geothermal heat exchanger simulation, which is fast, and of high fidelity.**
- **Design an unique geothermal heat exchanger, which is compact, efficient, and reduces cost for GHP.**
- **4 Phases**
  - Phase-1: Algorithm development and Validation (completed)
  - Phase-2: New advanced design analysis (completed, HGI proprietary)
  - Phase-3&4: Long term performance prediction (in discussions)

UT Computational Fluid Dynamics Laboratory



Hardin Geotech INC

Parabolic NS Formulation

- **Space-marching rather than time-marching solution**
- **Assumptions**
  - Steady and incompressible flows
  - Second derivative terms with respect to streamwise direction omitted
- **Derivations**
  - Series expansion with nondimensionlization (Tannehill et al 1997, Baker 1983 & 2010)

Parabolic NS Formulation

Fluid

$$\Lambda(\Theta) = w\frac{\partial\Theta}{\partial z} - \frac{1}{\mathrm{Re}\,\mathrm{Pr}}\left[\frac{\partial}{\partial x}\left((1+\kappa^T)\frac{\partial\Theta}{\partial x}\right) + \frac{\partial}{\partial y}\left((1+\kappa^T)\frac{\partial\Theta}{\partial y}\right)\right] = 0$$

Solid

$$\Lambda(\Theta) = -\ \kappa\left[\frac{\partial^2\Theta}{\partial^2 x} + \frac{\partial^2\Theta}{\partial^2 y}\right] = 0$$

Fluid+Solid

$$\Lambda(\Theta) = w\frac{\partial\Theta}{\partial z} - \frac{1}{\mathrm{Re}\,\mathrm{Pr}}\left[\frac{\partial}{\partial x}\left((\alpha+\kappa^T)\frac{\partial\Theta}{\partial x}\right) + \frac{\partial}{\partial y}\left((\alpha+\kappa^T)\frac{\partial\Theta}{\partial y}\right)\right] = 0$$

κ^T , ratio of turbulent to laminar thermal diffusivity

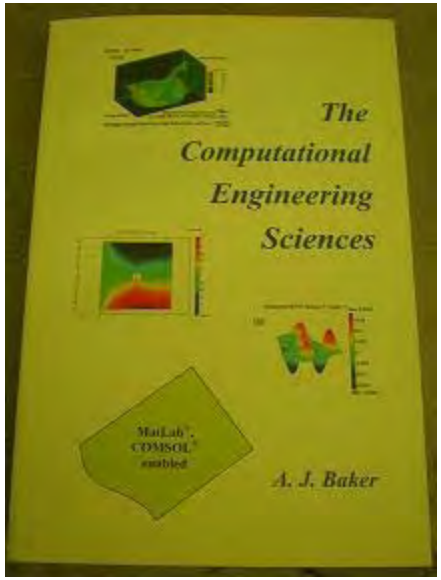
α = 1, fluid circuit

α = thermal diffusivity normalized by that of fluid, non-fluid components

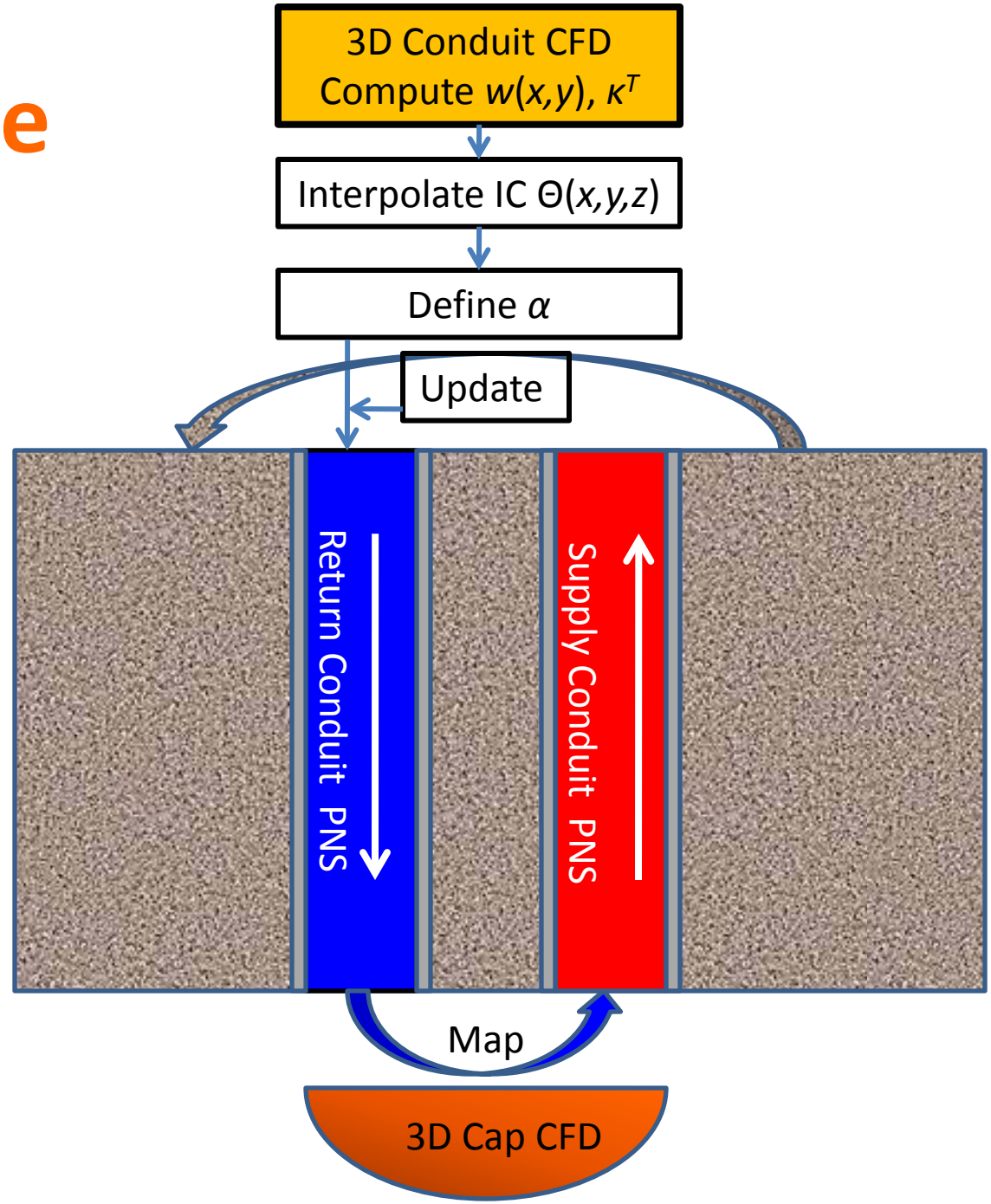
$\Theta = (T - T_C)/(T - T_H)$

FEM Implementation

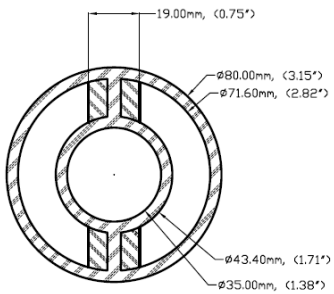
- **UT CFD Lab research code, aPSE**
  - Galerkin weak statement (GWS) algorithm
  - Bilinear finite element trial space basis
  - Preconditioned non-symmetric sparse matrix solver, GMRES



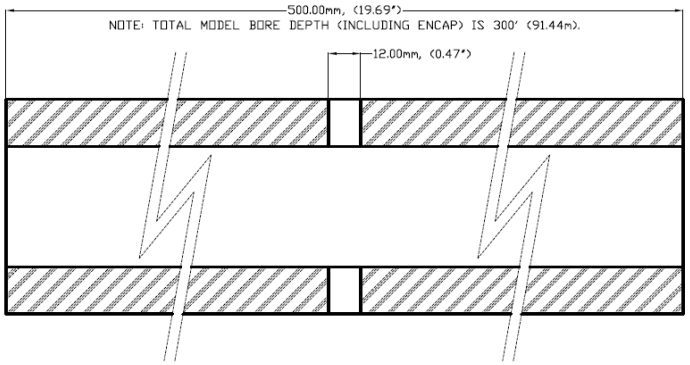
The Iterative Procedures



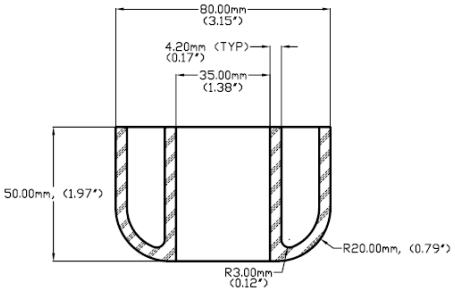
BiSec Geothermal Heat Exchanger



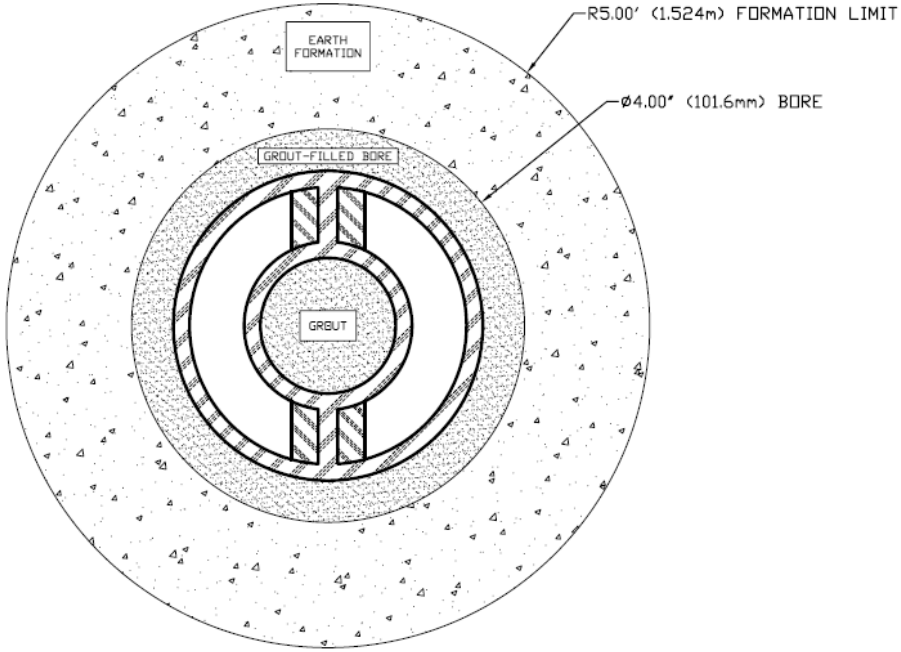
BiSec 3.2 EXCHANGER
RADIAL CROSS SECTION



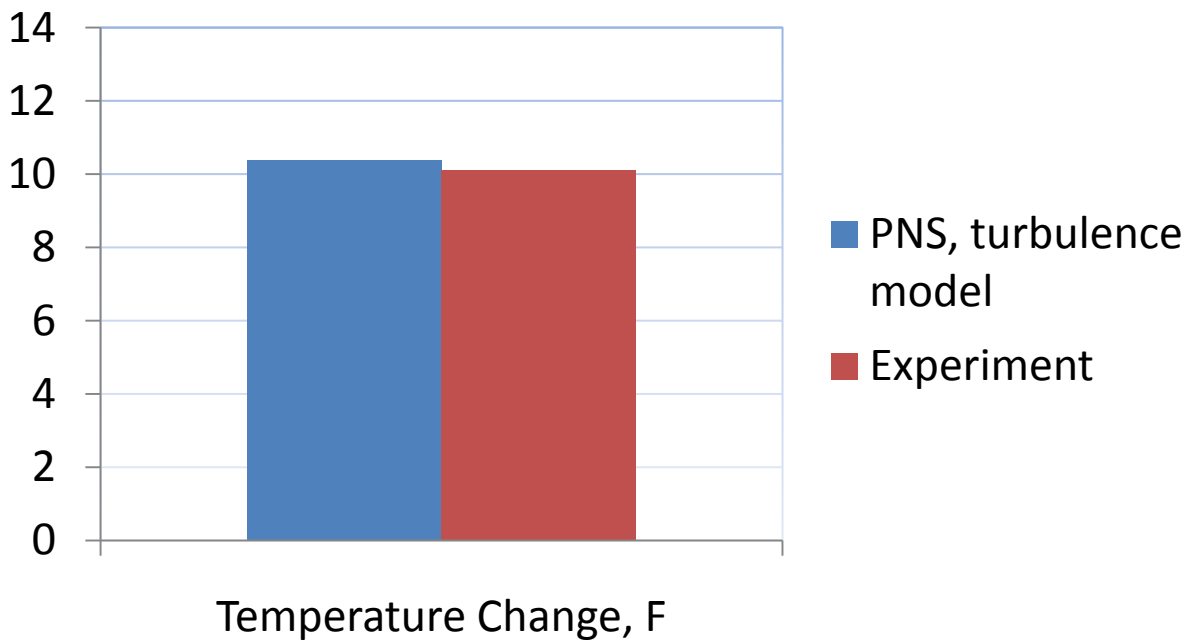
BiSec 3.2 EXCHANGER AXIAL CROSS SECTION
NOT TO SCALE.



BiSec 3.2 EXCHANGER END CAP
AXIAL CROSS SECTION

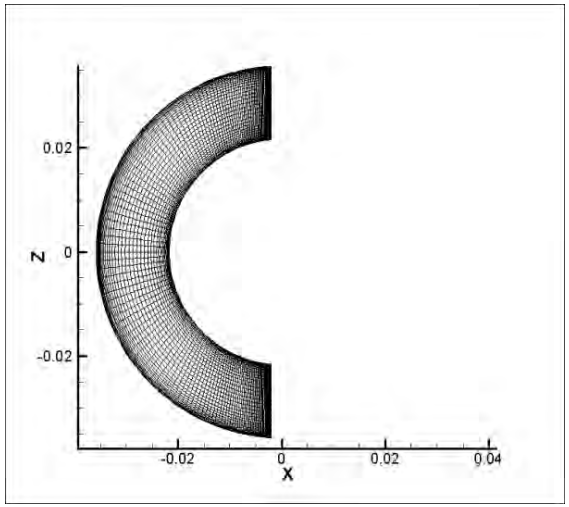


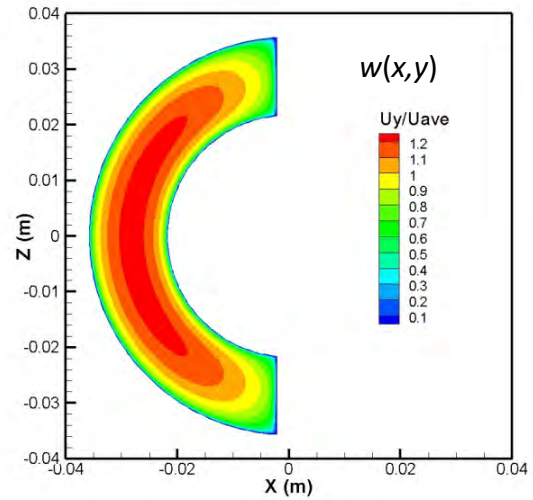
Validation with GHP 24-Hour Field Experiment (Error < 3%)

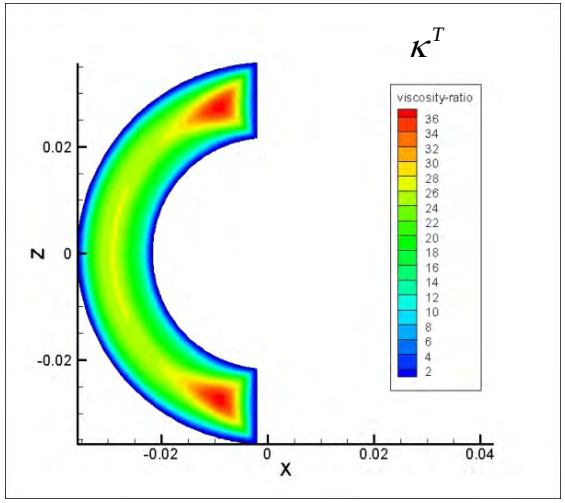


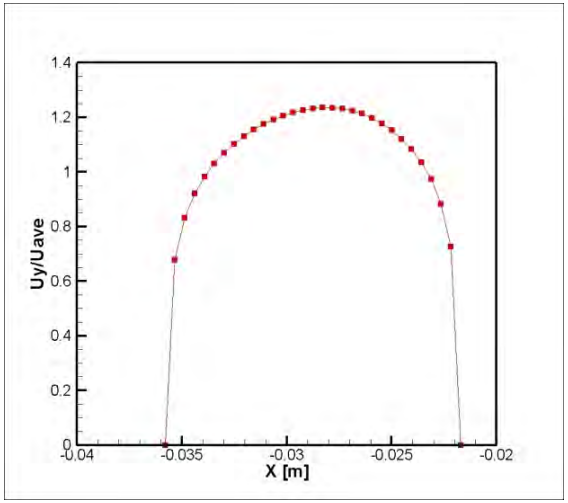
BiSec component	non-D thermal diffusivity	thermal diffusivity ratio α
piping	0.2176	1.435
grout	0.4663	3.070
formation	0.9735	6.562
fluid	0.1520	1.000

3D CFD Solution for Fully Developed Turbulent Flow, Re = 10,600



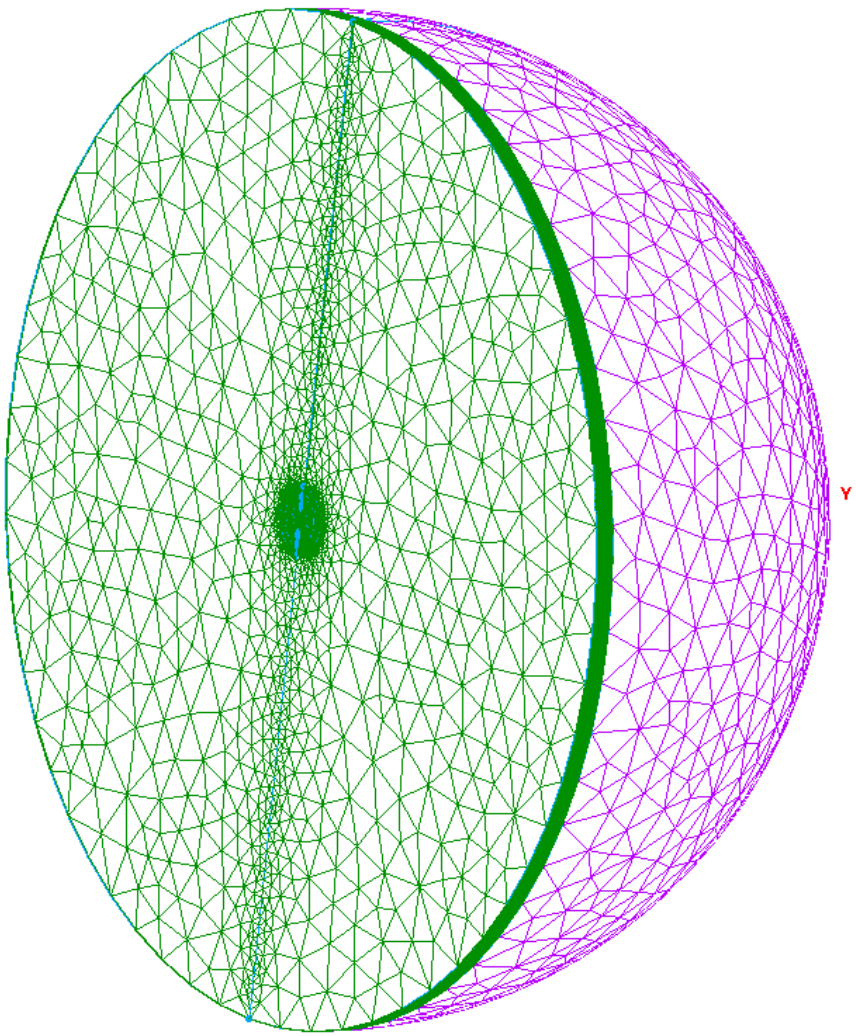


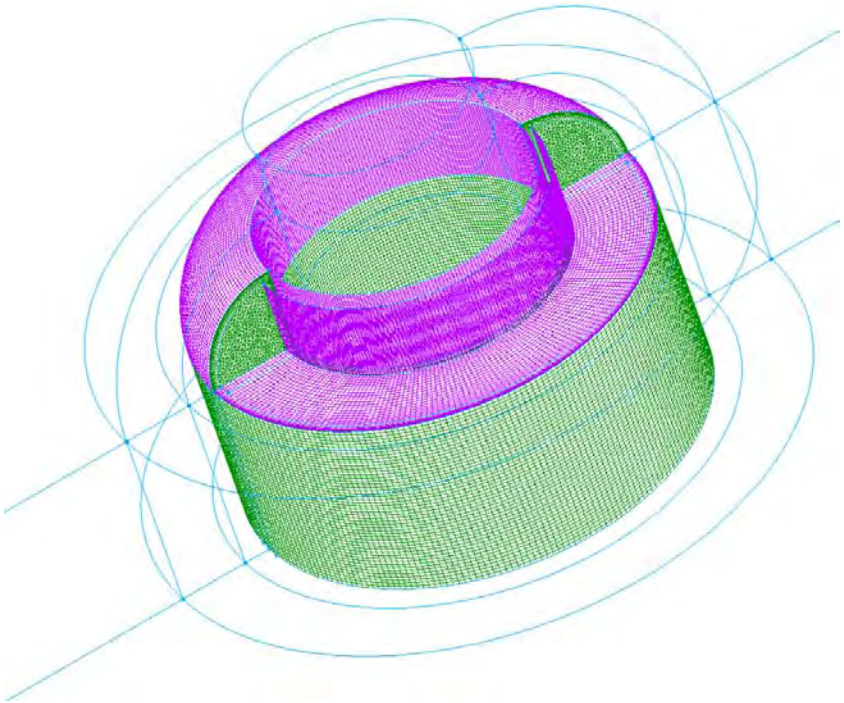




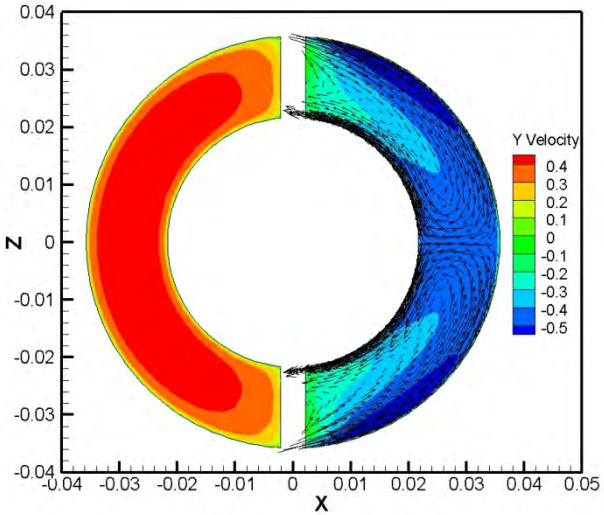
**Here, y=Z*

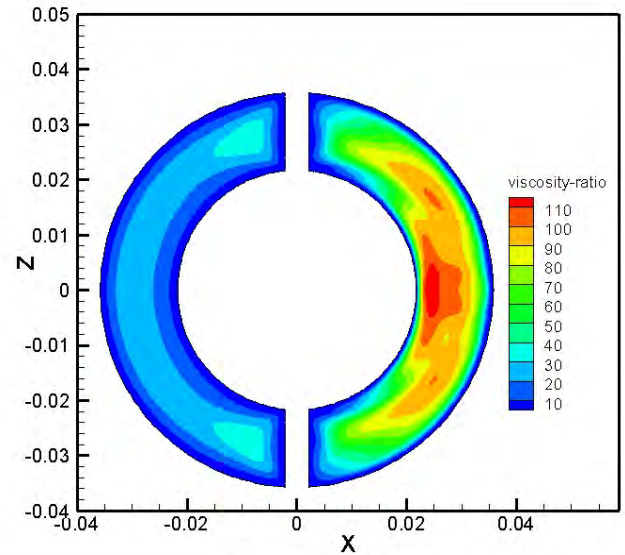
3D CFD Mesh for Cap Region Simulation

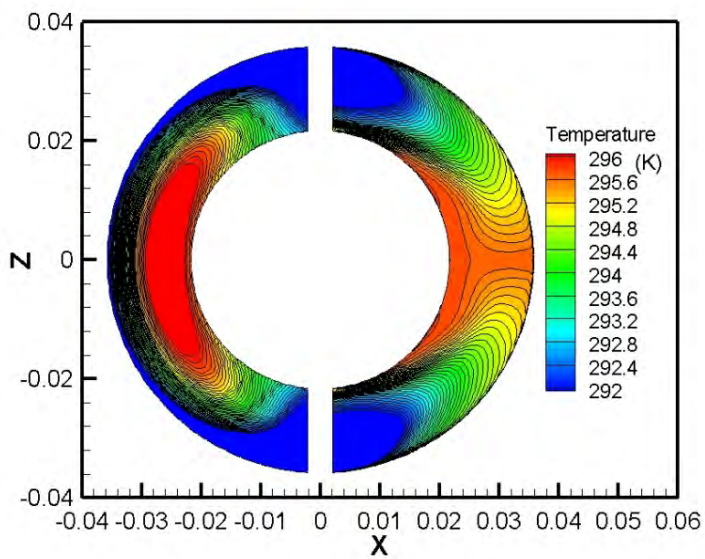




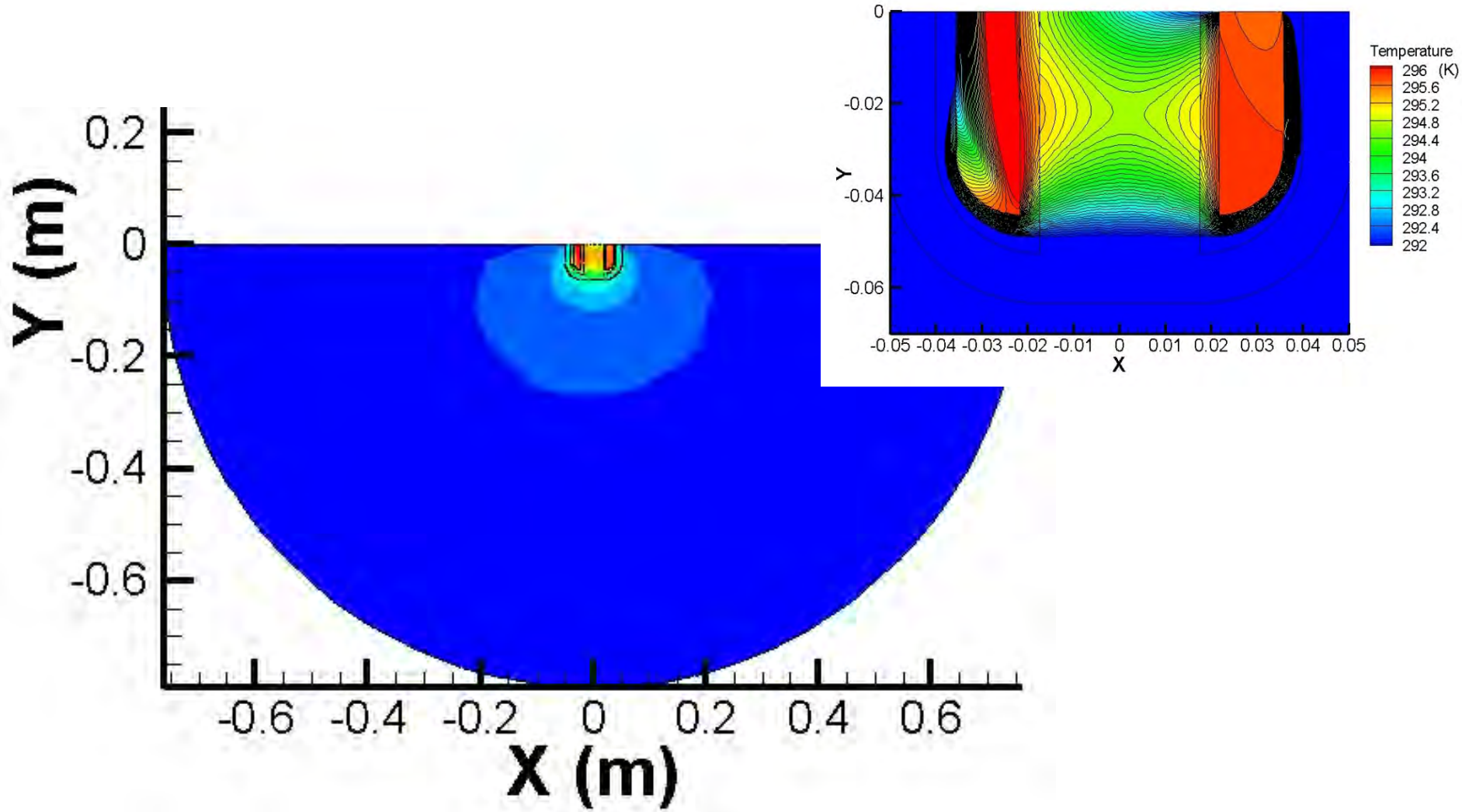
Numerical Results on Horizontal Plane Intersection of Cap and Conduits



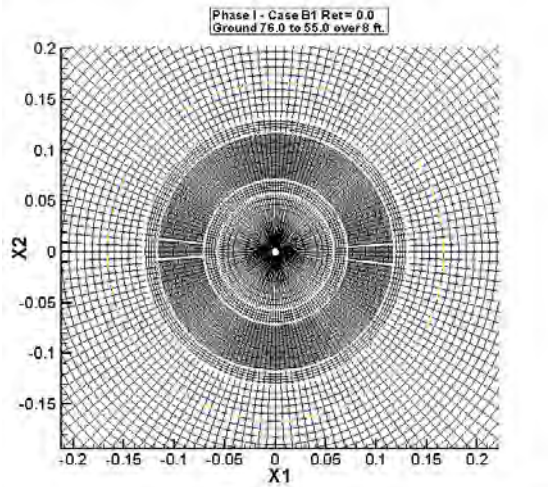


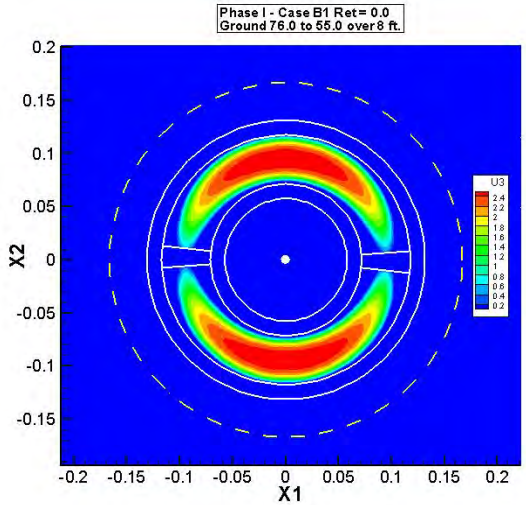


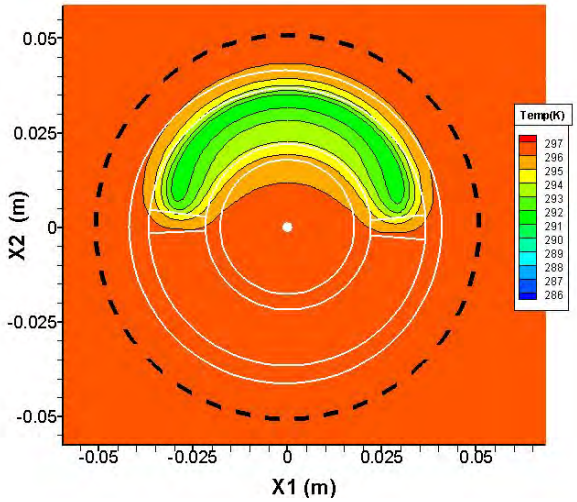
Numerical Results on Vertical Plane in/near the Cap



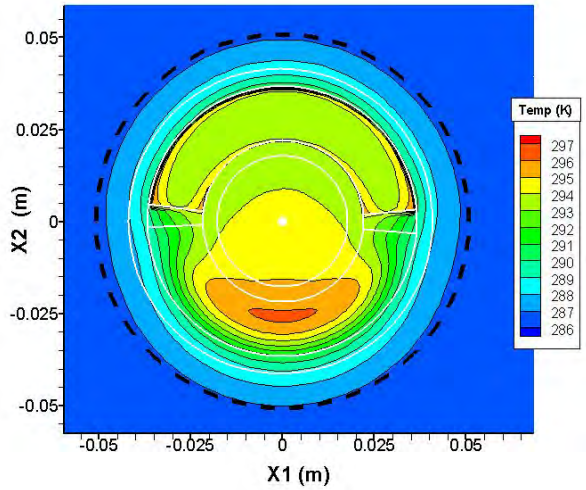
PNS Solutions for Laminar Flow in Conduits – For Algorithm Verification





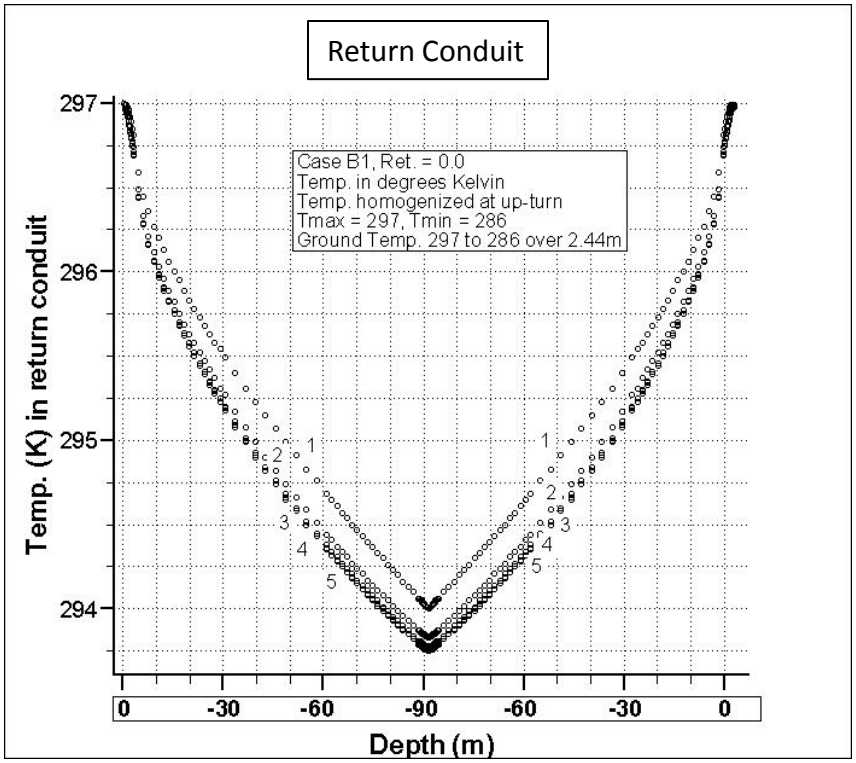


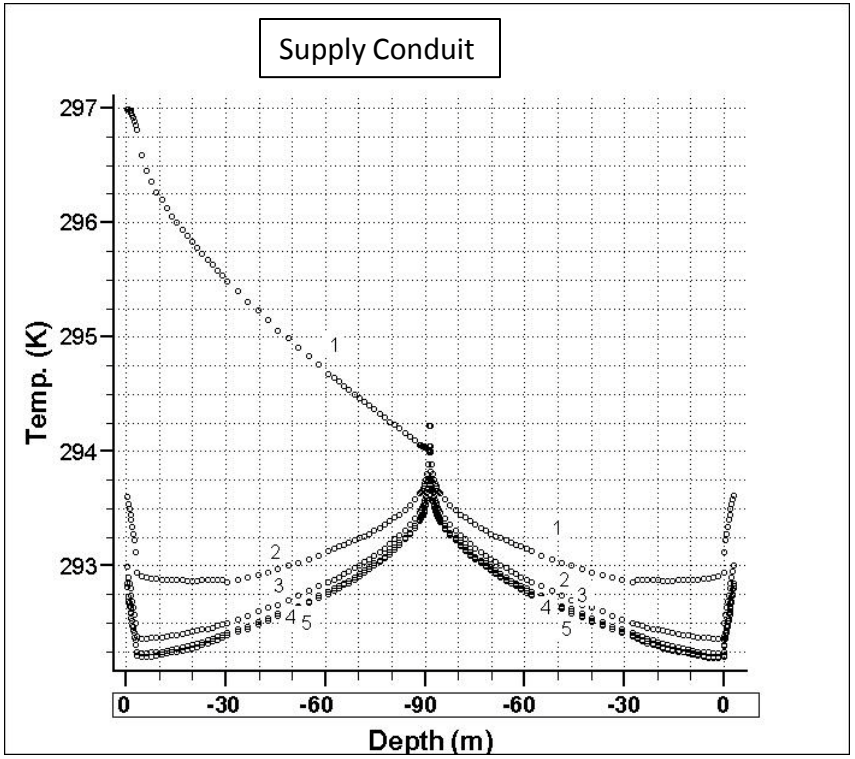
Inflow ground plane



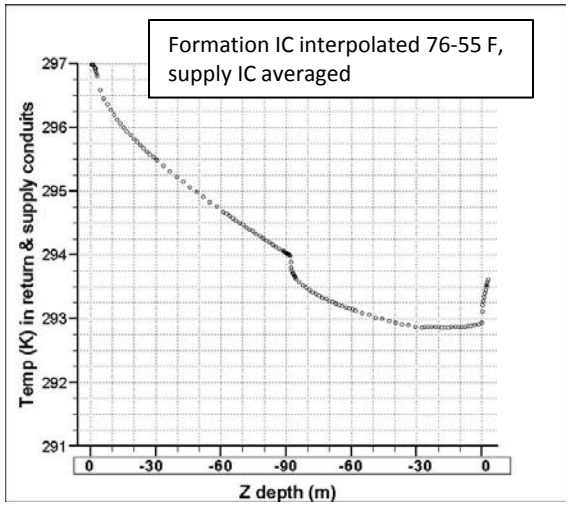
Cap-conduit interface

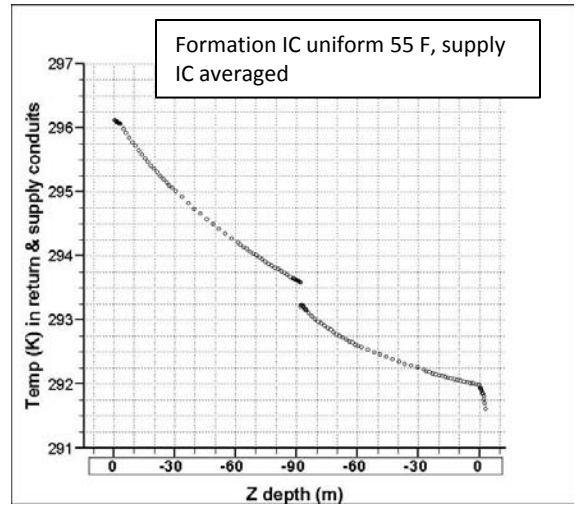
PNS Iterative Solution Sequence

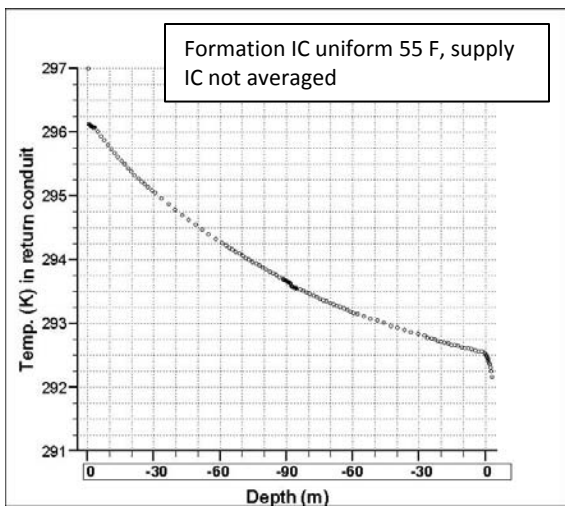


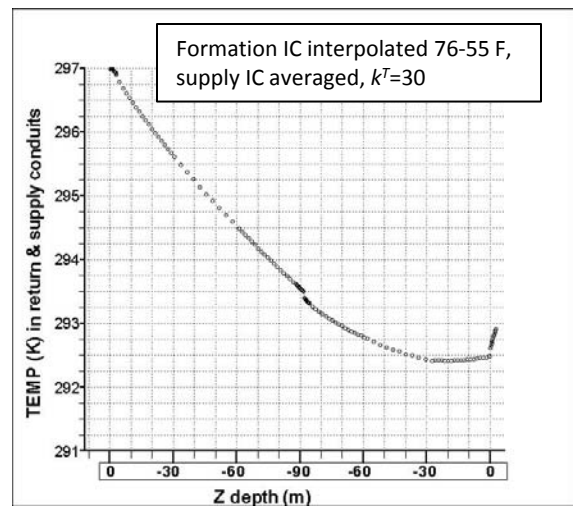


PNS Solution for Laminar/Turbulent Flow – Sensitivity of ICs



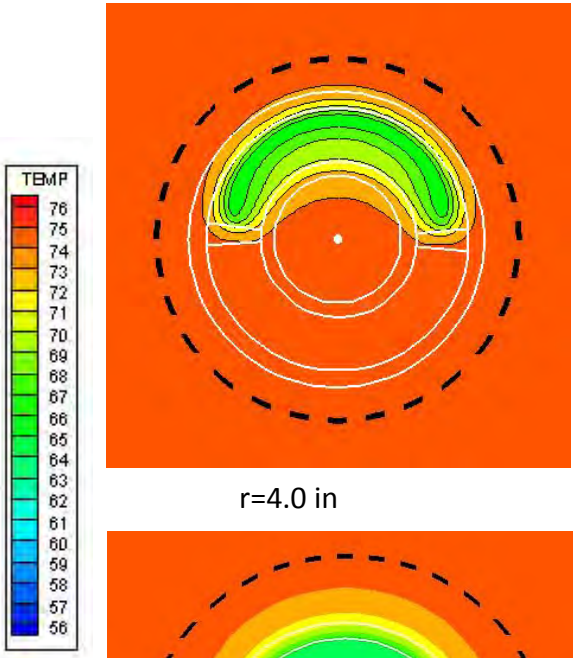




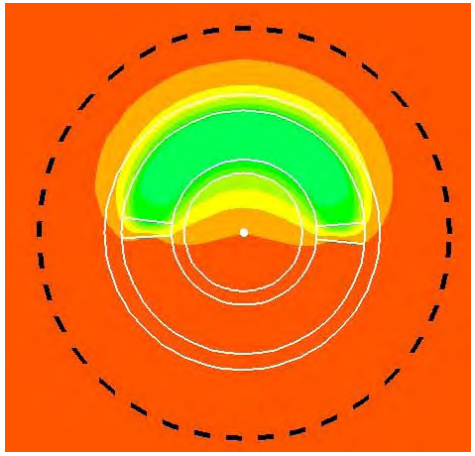


PNS Solution for Turbulent Flow – Effects of Grout Thickness

Inflow ground plane



r=4.0 in



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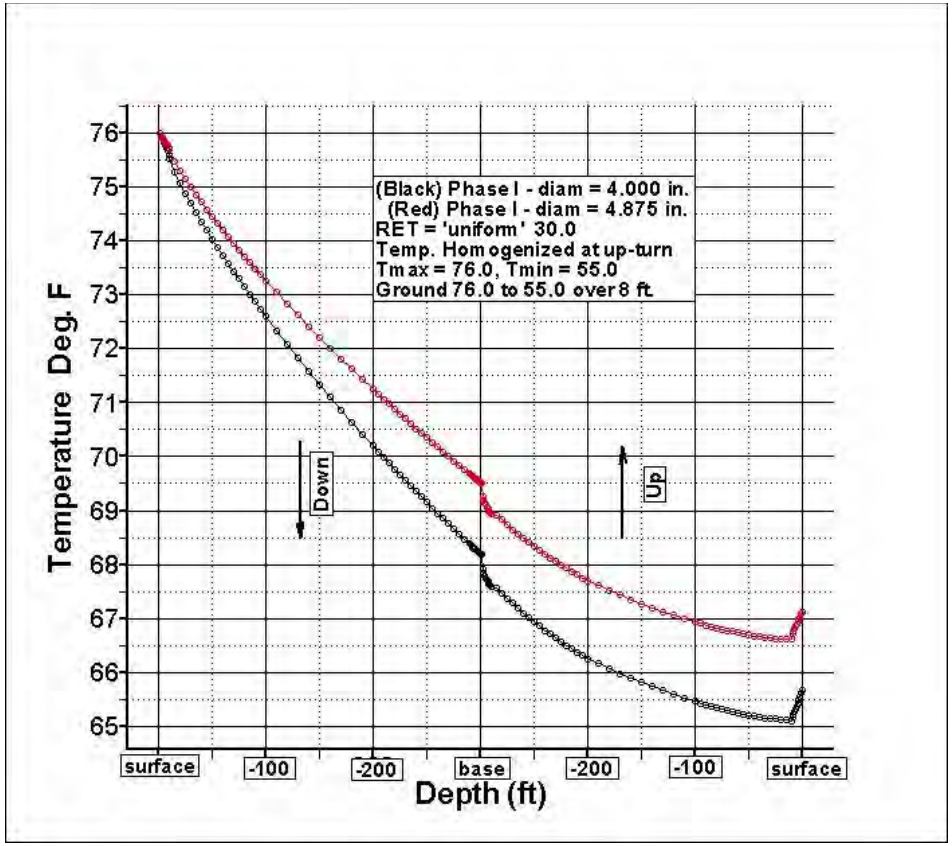

Conclusions

- **An effective iterative parabolic NS algorithm has been developed.**
- **PNS results agree very well with HGI GHP field experimental measurement.**
- **It has been demonstrated that the developed program can be used for new design and performance optimization of geothermal heat exchangers**
- **Within the examined parameter ranges, an analysis of a new compact geothermal heat exchanger shows:**
  - Fluid flow in return/supply conduits are in low-Re turbulent flow regime
  - Variation of temperature in the near-ground formation could cause considerable performance change
  - The increase of the grout thickness could result in significant performance loss. (When radius is increased by 22%, the performance is reduced by 15%).

Thank You!