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

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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

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
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

Heat Pump Operation Modes

Key Components
- Condenser
- Evaporator
- Expansion valve
- Compressor

(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

Single U-pipe
Pipe diameter = 25-32 mm
Width = 50-70 mm

Double U-pipe
Pipe diameter = 25-32 mm
Max. Width = 70-80 mm

Simple Coaxial
External diameter = 40-60 mm

Complex Coaxial
Max. width = 70-90 mm

(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

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

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

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

\[ Nu_s = 0.023 Re^{0.8} \cdot Pr^{0.4} \]
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 average 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**

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

**Energy**

\[ \frac{\partial}{\partial t} (\rho E) + \frac{\partial}{\partial x_i} [u_i (\rho E + p)] = \frac{\partial}{\partial x_j} \left[ \left( k + \frac{C_p \mu_i}{Pr_t} \right) \frac{\partial T}{\partial x_j} + u_j (\tau_{ij})_{eff} \right] + S_h \]

**Turbulence**

\[ \frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho u_i k) = \frac{\partial}{\partial x_i} \left[ (\mu + \mu_i / \sigma_k) \frac{\partial k}{\partial x_i} \right] - \rho \varepsilon \]

\[ + \mu_i \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_j}{\partial x_j} - 2\mu \left( \frac{\partial k}{\partial x_j} \right)^2 \]

**Low-Re Model**

\[ \frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_i} (\rho u_i \varepsilon) = \frac{\partial}{\partial x_i} \left[ (\mu + \mu_i / \sigma_\varepsilon) \frac{\partial \varepsilon}{\partial x_i} \right] + f_1 C_1 \frac{\varepsilon}{k} \mu_i \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_j}{\partial x_j} \]

\[ - f_2 C_2 \rho \varepsilon^2 \frac{2}{k} + 2\mu \left( \frac{\partial^2 u_i}{\partial x_j \partial x_j} \right)^2 / \rho \]

**Conduction**

\[ \rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i} \left( k_i \frac{\partial T}{\partial x} \right) \]
The Multiphysics Challenges

- Huge Scale Disparity
  - $L/D \sim 10^4$
- 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)
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
Parabolic NS Formulation

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

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

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

\(\kappa^T\), ratio of turbulent to laminar thermal diffusivity

\(\alpha = 1\), fluid circuit

\(\alpha = \) 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

3D Conduit CFD
Compute \( w(x,y), \kappa^T \)

Interpolate IC \( \Theta(x,y,z) \)

Define \( \alpha \)

Update

Map

3D Cap CFD

Return Conduit PNS

Supply Conduit PNS
BiSec Geothermal Heat Exchanger
Validation with GHP 24-Hour Field Experiment (Error < 3%)

![Bar chart showing temperature change with PNS, turbulence model and experiment results.]

<table>
<thead>
<tr>
<th>BiSec component</th>
<th>non-D thermal diffusivity</th>
<th>thermal diffusivity ratio α</th>
</tr>
</thead>
<tbody>
<tr>
<td>piping</td>
<td>0.2176</td>
<td>1.435</td>
</tr>
<tr>
<td>grout</td>
<td>0.4663</td>
<td>3.070</td>
</tr>
<tr>
<td>formation</td>
<td>0.9735</td>
<td>6.562</td>
</tr>
<tr>
<td>fluid</td>
<td>0.1520</td>
<td>1.000</td>
</tr>
</tbody>
</table>
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

Return Conduit

Case B1, Rot = 0.0
Temp. in degrees Kelvin
Temp. homogenized at up-turn
Temp = 297, Tmin = 286
Ground Temp. 297 to 286 over 2.44m

Supply Conduit
PNS Solution for Laminar/Turbulent Flow – Sensitivity of ICs

- Formation IC interpolated 76-55 F, supply IC averaged
- Formation IC uniform 55 F, supply IC averaged
- Formation IC uniform 55 F, supply IC not averaged
- Formation IC interpolated 76-55 F, supply IC averaged, $k^T=30$
PNS Solution for Turbulent Flow – Effects of Grout Thickness

Inflow ground plane

r=4.0 in

r=4.875 in
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!