Modeling of Standing Column Wells in Ground Source Heat Pump Systems

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Outline

- Introduction
- Model development
- Experimental validation
- Application example
- Conclusions and recommendations
SCW Systems

- **Standing Column Well:**
  - Single borehole
  - Open loop
  - Water extracted from and returned to same borehole
  - Similar to a domestic water well, but water is returned, for the most part.
  - In some systems, some water, some of the time, is not returned. ("Bleed")
Introduction

SCW systems

- Operation
  - Without bleed
  - With bleed

- Benefits
  - Economy, environmental benefits...
  - 50-60 feet per ton

- Limitation
  - Good groundwater quality
  - Local regulations
Previous work

- No models available for SCW design and energy analysis purposes:
  - Effects of bleed not quantified.
  - Time varying thermal boundary conditions
  - Effects of design parameters such as borehole diameter, borehole depth, dip tube size, etc. not quantified.
Model: Detailed model

- Detailed model (ASHRAE-RP1119)
  - Two-dimensional (radial/axial) finite volume method-composed of two coupled components
- Well borehole model
  - Heat transfer in the borehole
- Finite volume model
  - Heat transfer in the surrounding rock
  - Flow in the borehole and in the surrounding rock
Model: Detailed model

- Adiabatic surface
- Top of Water Table
- Return Pipe
- Discharge
- Borehole wall boundary condition is heat flux from sub-borehole model
- Suction Pipe Inlet

Head/temperature distribution after one year of normal operation

\[ T = (11.1 + 0.006 \times \text{depth}) \, ^\circ C \]

Head is set as constant zero

\[ T = 13.38 \, ^\circ C \]

Head is set as constant zero

( head flux is specified)
Model: Detailed model

- Significant Parameters
  - Bleed Rate; Borehole depth
  - Rock thermal conductivity and hydraulic conductivity
- Performance can be improved dramatically by introducing bleed
- As bleed rate increases, sensitivity to length decreases
- As hydraulic conductivity increases, there can be a tradeoff between convective and advective heat transfer
- Model takes several weeks (!) to simulate a single year of operation
Model: Simplified model

- **Simplified model**
  - One-dimensional finite difference method
  - For annual building simulation
    - More than a hundred thousand times faster than detailed model. 😊
- **Assumptions**
  - No vertical heat and water flow
  - Zero natural ground temperature gradient
Model: Simplified model

\[ T_{gw} \cdot b \cdot \dot{m} \]

\[ T_{fi} \cdot (1-b) \cdot \dot{m} \]

\[ T_{fo} \cdot \dot{m} \]

\[ \dot{m} b C_p T_{gw} \]

\[ \dot{m} (1-b) C_p T_{fi} \]

\[ \dot{m} C_p T_{fo} \]

Bleed flow at \( T_{fi} \)

Groundwater flow at \( T_{gw} \)

Wall

Far Field

Borehole

\( T_{far} = 12^\circ C \)
Model: Simplified model

- Three different effects of water on the heat transfer in SCW system
  - Static water
    - Effective thermal conductivity
  - Induced groundwater flow (w/o bleed)
    - Enhanced thermal conductivity
  - Bleed
    - Bleed-driven advection
Model: Simplified model

- Use enhanced thermal conductivity
- The effect of bleed is superimposed
- Three procedures to estimate the enhanced thermal conductivity
  - Physical *in-situ* test
  - Numerical *in-situ* experiment
  - Correlations
Comparisons of temperatures at the outlet to the well for the simplified model (SCW1D), reference model, and Mikler’s data in cooling and heating mode.

- Penn. State University
- One SCW without bleed
- 320 m (1050 ft) deep
- 0.1524 m (6 in) diameter

Experimental validation—without bleed
Experimental validation—Haverhill public library, Massachusetts

- Initially two SCWs, Now four SCWs
- 457 m (1500 ft) deep
- 0.1524 m (6 in) diameter
Comparisons of calculated and measured temperatures at the outlet of the well using the Haverhill Public Library installation data.
Application example

- Annual energy simulation implemented in HVACSIM+

- Three different system
  - Single U-tube closed-loop
    - Short-time step g-function
  - SCW without bleed
    - Simplified SCW 1D model
  - SCW with bleed – deadband control
    - Simplified SCW 1D model
Application example

Summary of ground heat exchanger design results for Boston weather file

<table>
<thead>
<tr>
<th>Ground Heat Exchanger Type</th>
<th>Borehole Geometry</th>
<th>Borehole Depth (m) [ft]</th>
<th>Required Total Borehole Length (m) [ft]</th>
<th>$EFT_{\text{max}}$ (°C) [°F]</th>
<th>$EFT_{\text{min}}$ (°C) [°F]</th>
<th>Feet per ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single U-tube closed-loop</td>
<td>$1 \times 8$</td>
<td>82 (268)</td>
<td>653 (2,144)</td>
<td>29.7 (85.5)</td>
<td>3.4 (38.2)</td>
<td>121</td>
</tr>
<tr>
<td>Standing Column Well Without Bleed</td>
<td>$1 \times 1$</td>
<td>391 (1,283)</td>
<td>391 (1,283)</td>
<td>22.8 (73.1)</td>
<td>7.0 (44.6)</td>
<td>72</td>
</tr>
<tr>
<td>Standing Column Well With 10% Bleed (Deadband Control)</td>
<td>$1 \times 1$</td>
<td>263 (863)</td>
<td>263 (863)</td>
<td>28.1 (82.5)</td>
<td>7.0 (44.6)</td>
<td>48</td>
</tr>
</tbody>
</table>
Application example

- Required total borehole depth for different ground heat exchanger systems in Boston, MA
  - SCW without bleed requires 40% less borehole depth
  - SCW with bleed requires 60% less borehole depth
Application example

Life Cycle Cost - 20-year Operation
(Present Value)

- Single U-tube
- SCW w/o bleed
- SCW w/ bleed

Cost ($)
Conclusions

- Developed numerical models of standing column wells
  - Two-dimensional finite volume model
  - One-dimensional finite difference model
- Validated against experimental data
  - With Bleed
  - Without bleed
- 1-d model is suitable for either energy analysis or design purposes.
Recommendations–Future Research

- Extend the model to account for well-to-well interference in multiple standing column well systems.
- Develop and validate complete design procedure, including recommended site tests:
  - *In situ* measurement of the thermal conductivity
  - Well drawdown test for the hydraulic conductivity
- Further long-term experimental validation
Any Questions?

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