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The correct citation for the paper is:

Simulation studies are presented to examine the thermal and economic performance of standing column wells with and without groundwater bleed in different locations in the United States. The simulations are based on a simplified standing column well model that has been integrated into an hourly building energy simulation program. The required design depth and energy costs from standing column well systems are compared with that of single U-tube closed-loop systems. Results show that the standing column well systems require less borehole length. A comparative life-cycle cost analysis is conducted considering 20 year system operation.

INTRODUCTION

Ground-source heat pump (GSHP) systems have been gaining increasing popularity in commercial and residential buildings due to their reduced energy and maintenance costs as compared with conventional systems (Spitler et al. 2002; Rees et al. 2004). GSHP systems that use groundwater circulated from wells as a heat source/sink are commonly known as standing column well (SCW) systems. The ground heat exchanger in such systems consists of a vertical borehole that is filled with groundwater up to the level of the water table (similar in construction to a domestic water well). Water is circulated from the well through the heat pump in an open-loop pipe circuit. A proportion of the water is returned to the well.

Compared with other GSHP systems, shorter borehole depths and more stable water temperatures make the SCW system an attractive commercial and industrial design approach. Now, there are approximately 1000 SCW installations in the United States. Most of them are located in the Northeast and Pacific Northwest in heating-dominated residential and light commercial applications. The vast majority of SCWs exist in the northeastern Appalachian region including Maine, Massachusetts, New Hampshire, New York, northwestern New Jersey, and portions of southeastern Canada (Orio et al. 2005). These regions have lower mean ground temperatures and higher heating loads than other areas, so at this time most SCW designs are focused on heat extraction.

In SCW systems, water is recirculated between the well and the building (heat pump). Deep bores are drilled in hard rock, creating a standing column of water from the static water level down to the bottom of the bore. Water is recirculated from one end of the column to the heat pump and back to the other end of the column (see Figure 1).

During peak heat rejection or extraction periods, if the well-water temperature drops too low or climbs too high, SCW systems can bleed part of the water rather than return it all to the well. This causes water to flow to the column from the surrounding formation to make up the flow. This cools the column and surrounding ground during heat rejection in the summer and heats the column and surrounding ground during heat extraction in the winter, thus restoring the well-water temperature to the normal operating range and improving the system performance. The bleed water can be diverted to a storm sewer, used for domestic water consumption, or otherwise disposed. Sometimes, SCW systems serve to provide household domestic water, which causes the system to naturally bleed the whole year. Because SCW systems utilize groundwater, they are regulated by state or local authorities and some locales may prohibit bleeding or otherwise regulate the design.

The objective of the work described in this paper is to examine the potential performance of SCW systems in differ-
ent locations of the United States. Practical simulation and design calculations require a computationally efficient model of the SCW. A simplified, one-dimensional SCW model has been developed by Deng (2004) and Deng et al. (2005) for use in hourly simulation programs or design tools. Several necessary assumptions to achieve reasonable computational speed for design and simulation purposes are used in the simplified SCW model, including zero natural ground temperature gradient, homogenous and isotropic aquifers, and density independent flow. Deng (2004) considered some limiting cases and concluded that errors caused by these assumptions are acceptable for either energy analysis programs or SCW design programs for the geological formations in which SCW systems are generally installed. Therefore, in this paper, SCW system performance is examined with a system simulation approach using this simplified model. For comparison purposes, SCW system performance is compared to that of a single U-tube closed-loop ground heat exchanger system, using the model developed by Yavuzturk and Spitler (1999). (Here, “single” refers to the fact there is only one U-tube in each borehole.)

System performance is examined for a single building type at five different locations in the United States that appear to have suitable hydrogeology (Orio et al. 2005) for SCW systems. Both system types have many degrees of freedom in the design, and no attempt to optimize either system has been made. For example, in the closed-loop system, the number of boreholes, borehole depth, antifreeze mixture, grout thermal conductivity, etc., are all design variables that interact with each other. Likewise, in the SCW system, the well depth, bleed rate, bleed control strategy, etc., are all interacting design variables. Rather than attempting to develop optimal designs for both system types, typical system designs for both system types have been used. In order to retain some fairness in the comparisons, the SCW and closed-loop boreholes were both sized to maintain a fixed safety margin of 2°C (3.6°F) between the minimum exiting fluid temperature from the heat pump and the working fluid freezing point.

Rather than drawing ultimate conclusions about the relative performances of the two system types, which will vary with ground thermal and hydrological properties, building loads, system design parameters, etc., this study illustrates how the comparisons might be made. All of the system models are currently available in one modeling environment (Clark 1985), and most of the system models have either already been transferred to other environments, such as EnergyPlus, or may be expected to be transferred in the near future, allowing designers to make their own comparisons.

**METHODOLOGY**

In this paper, the performance comparisons of the SCW and closed-loop GSHP systems are accomplished by means of a system simulation approach using the HVACSIM+ (Clark 1985) modeling environment. The core component models for the SCW system are a standing column well model (Deng et al. 2005; Deng 2004), a simple water-to-air heat pump model, and a simple circulating water pump. For the closed-loop GSHP system, the SCW model is replaced with a ground heat exchanger model. The system simulations were made by connecting individual component models in a graphical user interface (Varanasi 2002) for HVACSIM+ (Clark 1985). The system simulations are performed using a small office building located in different climatic regions of the United States. The hourly heating and cooling building loads are determined by a building energy simulation program (BLAST 1986) and are treated as thermal boundary conditions in the HVACSIM+ environment.

For both system types, there are three component models. Water temperatures leaving the well calculated by the SCW model (or closed-loop ground heat exchanger model) are used as inputs (water temperatures returning to the heat pump) to the heat pump model. Water temperatures leaving the heat pump are treated as inputs to the circulating pump model. Water temperatures leaving the circulating pump model are used as inputs to the SCW model (or closed-loop ground heat exchanger model). The water pump model uses the system pressure drop calculated from the SCW model (or closed-loop ground heat exchanger model) and heat pump model to calculate energy consumption.

**The SCW Model**

The SCW model used in this study is that developed by Deng (2004) and Deng et al. (2005), which is a simplified one-dimensional numerical model. This model simulates groundwater flow and heat transfer in and around the SCW. Both groundwater flow induced by pumping without bleed and that induced by bleed are considered in this model. An “enhanced”
thermal conductivity is used to consider the water flow caused by the pumping and buoyancy. This simplified model represents bleed-driven advection explicitly. When bleed occurs, the effect of bleed is superimposed on top of the effects of pumping and buoyancy. The simplified one-dimensional numerical model has two submodels:

- Thermal and fluid energy transport in the surrounding rock are dealt with in a one-dimensional (radial) finite difference model, which solves the general one-dimensional advection-diffusion equation with enhanced thermal conductivity. Borehole wall temperature is determined by this model.
- Thermal energy transport in the borehole is handled by a thermal network model, where the fluid in the borehole is treated as a single node. Water temperature back to heat pump is calculated by this borehole model.

Three approaches to estimate “enhanced” thermal conductivity were described in detail by Deng (2004):

- Physical in situ test
- Numerical in situ experiment
- Correlations for enhanced thermal conductivity

The last two approaches involve use of the detailed two-dimensional numerical model (Spitler et al. 2002; Rees et al. 2004). In this work, the “enhanced” thermal conductivity was estimated with the second approach.

In this study, deadband bleed control strategy is used during bleed operation. In winter, when exiting water temperature is lower than 8°C (46.4°F), bleed is started. When exiting water temperature is higher than 10.8°C (51.4°F), bleed is stopped. In summer, bleed is started when exiting water temperature is higher than 29.2°C (84.5°F) and stopped when exiting water temperature is lower than 26.4°C (79.5°F).

The Heat Pump Model

To match the peak building loads of the hypothetical building, two commercially available water-to-air heat pumps with a nominal capacity of 6 tons each were selected (see Tables 1 and 2). This water-to-air heat pump model is modeled in HVACSIM+ using a polynomial equation fit (see Equations 1 and 2).

\[
HP_{\text{capacity}} = C_1 + C_2 \cdot EFT + C_3 \cdot EFT^2
\]

\[
HP_{\text{power}} = C_4 + C_5 \cdot EFT + C_6 \cdot EFT^2
\]

It was assumed that the heat pump performance changed only with entering water temperatures. Curve-fits describing capacity vs. entering water temperature and power consumption vs. entering fluid temperature, at a range of flow rates, were derived from catalog data.

Inputs to this heat pump model include building loads, entering fluid temperatures, and fluid mass flow rates. The model computes the heat of rejection in cooling mode, the heat of absorption in heating mode, and the heat pump energy consumption. Outputs include exiting fluid temperature and energy consumption.

The Water Pump Model

The circulating water pump was assumed to have a constant 65% efficiency. Inputs to this model include system pressure drop, fluid mass flow rate, and building loads. The model calculates power consumption of the circulating water pump as follows.

\[
w = \frac{\rho g Q H}{\eta}
\]

where
\[
\rho = \text{the water density (kg/m}^3\text{)}
\]
\[
Q = \text{the volume flow rate (m}^3\text{/s)}
\]
\[
H = \text{the total dynamic head (m)}
\]
\[
\eta = \text{the efficiency of the circulating water pump, taken as}
\]
\[
0.65 \text{ for this model (Rafferty 1998)}
\]
\[
w = \text{the power consumption of the circulating water pump (W)}
\]

The circulating water pump model also calculates the exiting fluid temperature, although the temperature rise is negligible for all cases in this study.

The Single U-Tube Closed-Loop Ground Heat Exchanger Model

The single U-tube vertical closed-loop ground heat exchanger model used in this study for comparison is that developed by Yavuzturk and Spitler (1999), which is an extension of the long time-step temperature response factor model of Eskilson (1987). It is based on dimensionless, time-dependent temperature response factors known as \textit{g-functions}, which are unique for various borehole field geometries. The model includes a hierarchical load aggregation algorithm that

| Table 1. Coefficients for the 6 Ton Heat Pump (SI Units) |
|---|---|---|---|---|---|
| Heating mode | Cooling mode |
| C1 | C2 | C3 | C4 | C5 | C6 |
| 16186 | 489.8 | -2.88 | 6417 | 8.73 | 1.07 |
| 25393 | -180.6 | -0.48 | 4472 | 73.10 | 0.08 |

| Table 2. Coefficients for the 6 Ton Heat Pump (I-P Units) |
|---|---|---|---|---|---|
| Heating mode | Cooling mode |
| C1 | C2 | C3 | C4 | C5 | C6 |
| 22411 | 1123 | -3.03 | 6131 | -16.30 | 0.33 |
| 97443 | -332.8 | -0.15 | 3198 | 39.03 | 0.03 |
significantly reduces computation time. A detailed description of the model can be found in Yavuzturk (1999). The initial size of the single U-tube closed-loop ground heat exchanger was chosen with a commercial ground heat exchanger design tool (Spitler 2000).

Building Description and Load Calculation

A small building physically located in Stillwater, Oklahoma, was chosen for simulating the performance of the ground heat exchangers. The building loads are determined using building energy simulation software (BLAST 1986) with Typical Meteorological Year (TMY) weather files from different regions. The annual building loads for Boston, Massachusetts, are shown in Figure 2. In addition to Boston, other locations studied are Concord, New Hampshire; Harrisburg, Pennsylvania; Portland, Oregon; and Birmingham, Alabama. The total area of the building is approximately 1,320 m² (14,205 ft²). This building has previously been used in other energy studies (Yavuzturk 1999; Deng 2004), and several assumptions have been made to determine the annual building loads:

1. The building is divided into eight different thermal zones.
2. For each zone, a single zone draw-through fan system is specified. The total coil loads obtained from system simulation are equal to the loads to be met with the GSHP system.
3. Assume one person with a 70% radiant heat gain of 131.9 W (450 Btu/h).
4. 11.8 W/m² (3.75 Btu/h·ft²) of equipment plug load is used.
5. The lighting loads vary between 10.04 W/m² (3.17 Btu/h·ft²) and 15.88 W/m² (5.02 Btu/h·ft²) in the different zones.
6. Schedules for people occupancy, lighting, and equipment are specified.

Simplified Design Procedures

There are many degrees of freedom in the design of either SCW or closed-loop GSHP systems. In order to systematically compare the two system types, a simplified design procedure has been developed. The procedure is illustrated in Figure 3 and described below. Again, as discussed in the introduction, the goal is to make a comparison between typical system designs rather than optimized system designs.

The following assumptions are used during the ground heat exchanger design procedure.

1. A ground heat exchanger design tool (Spitler 2000) is used to size the vertical U-tube heat exchanger for given building load profiles. The closed-loop system uses an antifreeze mixture of 12.9% propylene glycol by weight, which has a −3.9°C (25°F) freezing point. Naturally, different concentrations of antifreeze will affect the sizing results and system performance, but this has been chosen as a reasonably typical value and applied in every case, even though different locations might have different optimal concentrations, perhaps even zero in Birmingham. The water in the SCW is, of course, untreated.
2. The safety margin for the freezing point temperature is 2°C (3.6°F). The fluid temperature drop across the heat pump at the design heating load is 5°C (9°F).
3. The resulting design minimum entering fluid temperatures to the heat pump are 3.1°C (37.6°F) and 7°C (44.6°F) for the single vertical U-tube closed-loop system and the SCW system, respectively.
4. The vertical U-tube closed-loop ground heat exchanger model described by Yavuzturk and Spitler (1999) is applied in the HVACSIM+ environment. The size of U-tube closed-loop ground heat exchanger and g-functions from a ground heat exchanger design tool (Spitler 2000) are used as input parameters for this model. After coupling with the given building load, the fluid temperatures back to the heat pump are calculated with this model.
5. The simplified one-dimensional numerical SCW model developed by Deng (2004) is applied in the HVACSIM+

![Figure 2](image)

*Figure 2* Building heating/cooling loads in Boston (positive loads are heating loads).

![Figure 3](image)

*Figure 3* Flow chart for simplified design procedure.
Economic Analysis Procedure

It is the economic benefit that makes the SCW system attractive. A perfect economic analysis is not possible considering the large variations in drilling costs across the United States (Yavuzturk and Chiasson 2002). However, a simple economic analysis is performed to give some insight into the benefits of SCW systems compared with single U-tube vertical closed-loop systems.

The net present value is calculated for the initial cost and 20-year operating cost. The net present value is based on the following assumptions (Yavuzturk and Chiasson 2002).

1. The installation cost per meter of borehole for a single U-tube ground heat exchanger is assumed to be $19.69 per meter of borehole, including trenching and headering.

2. The installation cost per meter of borehole for SCW systems is assumed to be $17.88 per meter of borehole, including trenching and headering.

3. The cost per meter of borehole is broken into drilling costs (including pipe installation, trenching, and headering), pipe costs (material only), and grouting costs (labor and materials). For the SCW system, costs of the grout used to seal the top of the well were neglected. Table 3 lists unit installation cost breakdowns for single U-tube closed loop and SCW systems.

4. A 6% annual percentage interest rate is used for the present value analysis.

5. The annual operating cost is based on electricity consumption for the first year of operation, calculated with the simulation. For the SCW system, water temperatures remain fairly stable from year to year, so little change in electricity consumption is expected. For the closed-loop system, loop temperatures will rise or fall over the years, depending on the balance between heat rejection and heat extraction. This will, in turn, cause a minor increase in the electricity consumption, which is not accounted for here.

6. The cost of electricity (DOE 2005) is listed in Table 4 for each of the states and is assumed to apply to the corresponding city.

7. Neither maintenance costs nor disposal costs are included in the life-cycle cost analysis.

SIMULATION RESULTS AND DISCUSSIONS

In this section, simulation results for a building using different ground heat exchanger systems (i.e., a single U-tube closed-loop system, an SCW system without bleed, and an SCW system with bleed) are presented and compared with annual operating costs for different states.

Table 4. Electric Utility Monthly Average Cost per Kilowatt-Hour for Commercial Buildings in Different States (Cents per Kilowatt-Hour)

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MA</td>
<td>7.8</td>
<td>7.5</td>
<td>7.8</td>
<td>8.5</td>
<td>8.7</td>
<td>9.8</td>
<td>10.2</td>
<td>10.1</td>
<td>10.7</td>
<td>9.5</td>
<td>8.6</td>
<td>8.7</td>
</tr>
<tr>
<td>OR</td>
<td>5.0</td>
<td>5.0</td>
<td>5.1</td>
<td>5.2</td>
<td>5.2</td>
<td>5.1</td>
<td>5.1</td>
<td>5.1</td>
<td>5.2</td>
<td>5.2</td>
<td>5.2</td>
<td>5.1</td>
</tr>
<tr>
<td>PA</td>
<td>5.9</td>
<td>5.7</td>
<td>5.9</td>
<td>5.8</td>
<td>5.7</td>
<td>7.2</td>
<td>6.6</td>
<td>6.6</td>
<td>6.6</td>
<td>6.2</td>
<td>6.0</td>
<td>6.7</td>
</tr>
<tr>
<td>AL</td>
<td>6.4</td>
<td>6.4</td>
<td>7.0</td>
<td>7.0</td>
<td>6.5</td>
<td>6.5</td>
<td>7.5</td>
<td>7.5</td>
<td>7.6</td>
<td>7.5</td>
<td>7.15</td>
<td>7.25</td>
</tr>
<tr>
<td>NH</td>
<td>11.1</td>
<td>11.2</td>
<td>11.2</td>
<td>11.4</td>
<td>11.7</td>
<td>11.3</td>
<td>11.6</td>
<td>11.3</td>
<td>11.6</td>
<td>11.2</td>
<td>10.7</td>
<td>11.0</td>
</tr>
</tbody>
</table>

Table 3. Installation Costs For Different Ground Heat Exchanger Systems ($/m borehole)

<table>
<thead>
<tr>
<th>Unit Installation Costs for Ground Heat Exchanger System ($/m borehole)</th>
<th>Single U-Tube Closed-Loop</th>
<th>Standing Column Well</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drilling, trenching, pipe handling, and installation</td>
<td>$15.75</td>
<td>$17.23</td>
</tr>
<tr>
<td>Pipe materials</td>
<td>$1.97</td>
<td>$0.65</td>
</tr>
<tr>
<td>Grout materials and placement</td>
<td>$1.97</td>
<td>$-</td>
</tr>
<tr>
<td>Total unit installation cost</td>
<td>$19.69</td>
<td>$17.88</td>
</tr>
</tbody>
</table>
SCW system with bleed) are described. First, one case in Boston is discussed in detail. Then, the simulation results for other cities are presented and discussed.

**Boston, MA**

The ground heat exchanger design parameters used in this study, including the borehole thermal resistance values for each case, are summarized in Table 5. The ground conditions are assumed to be similar to those in the northeast of the United States (northeastern Appalachians region). The simplified design procedure described previously was used here.

In Table 5, the borehole thermal resistance for a single U-tube vertical closed-loop system is calculated from a ground heat exchanger design tool (Spitler 2000), and the SCW system without bleed reduces the required depth by 40.1%, and the system with bleed reduces the required depth by 59.7%. The importance of the bleed is clear—the SCW system without bleed requires about 50% greater well depth than the SCW system with bleed. The SCW system can therefore significantly reduce capital costs, particularly the drilling costs, compared to a closed-loop system.

**Table 5. Summary of Ground Heat Exchanger Design Parameters for Boston, MA**

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Single U-Tube Closed-Loop</th>
<th>SCW (Without Bleed)</th>
<th>SCW (With 10% Bleed)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geologic conditions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock type</td>
<td>Fractured igneous and metamorphic rock</td>
<td>Fractured igneous and metamorphic rock</td>
<td>Fractured igneous and metamorphic rock</td>
</tr>
<tr>
<td>Thermal conductivity, W/m·K (Btu/h·ft·°F)</td>
<td>3.0 (1.73)</td>
<td>3.5 (Enhanced) (2.02)</td>
<td>3.5(Enhanced) (2.02)</td>
</tr>
<tr>
<td>Vol. heat capacity, J/m³·°C (Btu/ft³·°F)</td>
<td>2,600,000 (38.78)</td>
<td>2,600,000 (38.78)</td>
<td>2,600,000 (38.78)</td>
</tr>
<tr>
<td>Undisturbed earth temperature, °C (°F)</td>
<td>12.2 (53.96)</td>
<td>12.2 (53.96)</td>
<td>12.2 (53.96)</td>
</tr>
<tr>
<td>Water table depth, m (ft)</td>
<td>5 (16.41)</td>
<td>5 (16.41)</td>
<td>5 (16.41)</td>
</tr>
<tr>
<td><strong>Borehole</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter, m (in.)</td>
<td>0.11 (4.33)</td>
<td>0.1524 (6)</td>
<td>0.1524 (6)</td>
</tr>
<tr>
<td>Depth, m (ft)</td>
<td>81.68 (268)</td>
<td>391 (1,283)</td>
<td>263 (863)</td>
</tr>
<tr>
<td>Borehole geometry</td>
<td>1 × 8</td>
<td>Not applicable</td>
<td>Not applicable</td>
</tr>
<tr>
<td><strong>U-tube (high density polyethylene)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter inner, m (in.)</td>
<td>0.025 (1)</td>
<td>Not applicable</td>
<td>Not applicable</td>
</tr>
<tr>
<td>U-tube shank spacing, m (in.)</td>
<td>0.0367 (1.44)</td>
<td>Not applicable</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Thermal conductivity, W/m·K (Btu/h·ft·°F)</td>
<td>0.3895 (0.225)</td>
<td>Not applicable</td>
<td>Not applicable</td>
</tr>
<tr>
<td><strong>Grout</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Standard Bentonite</td>
<td>Not applicable</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Thermal conductivity, W/m·K (Btu/h·ft·°F)</td>
<td>0.7443 (0.433)</td>
<td>Not applicable</td>
<td>Not applicable</td>
</tr>
<tr>
<td><strong>Borehole thermal resistance</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_{borehole}, °C/W/m (°F/[Btu/h]/ft)$</td>
<td>0.1398 (0.2419)</td>
<td>0.0011 (0.0019)</td>
<td>0.0011 (0.0019)</td>
</tr>
</tbody>
</table>

**Table 6. 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>$EFT_{max}, °C (°F)$</th>
<th>$EFT_{min}, °C (°F)$</th>
<th>Feet per Ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single U-tube closed-loop</td>
<td>1 × 8</td>
<td>81.68 (268)</td>
<td>653.44 (2,144)</td>
<td>29.7 (85.5)</td>
<td>3.4 (38.2)</td>
<td>121</td>
</tr>
<tr>
<td>SCW without bleed</td>
<td>1 × 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>SCW with 10% bleed (deadband control)</td>
<td>1 × 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>
Figure 5 shows the breakdown in 20-year life-cycle costs for the different ground heat exchanger options in Boston. The results show that the operating costs are fairly similar. This is to be expected, as the systems were designed to similar minimum entering fluid temperatures, and therefore the entering fluid temperatures over the year do not differ widely. As a result, the heat pump power consumption is similar for all three systems, though it is marginally higher for the closed-loop system, as its design entering fluid temperature was lower than the SCW systems. The capital costs are significantly different, though, because of the different required borehole depths for the two system types.

It may be expected that the circulating water pump costs for the SCW system are greatly dependent on the water table depth. Based on the study described by Rees et al. (2004) and Deng (2004), which utilized continuous bleed, when the water table is shallow (i.e., 5 m [16 ft]), the circulating water pump cost difference between SCW systems with bleed and without bleed is very small, but if the water table is deeper (i.e., 30 m [98 ft]), circulating water pump costs for bleed cases with higher bleed rates are much higher than non-bleed cases. The same study also shows that for constant and continuous bleed operation, when the water table is low, on the order of 30 m (98 ft), the benefits of higher rates of bleed (> 10% in the study by Deng [2004]) are outweighed by the increased pumping costs.

However, when the SCW system in this study is in bleed control operation, increased bleed rate (in the range from 0% to 20%) will result in improved performance of the SCW system, regardless of the water table depth. Figure 6 shows annual energy costs for the SCW system with deadband bleed control with different bleed rates and water table depths in Boston. Table 7 gives the annual energy cost breakdowns for those cases. These simulations show that there are relatively small differences in circulating pump energy consumption for different bleed rates at the same water table depth. In fact, for the shallow water table depth, the differences disappear when the costs are rounded to the nearest dollar.

Likewise, the difference in water table depth shows smaller effects on circulating pump energy consumption than earlier studies (Deng 2004; Rees et al. 2004). This is because the bleed control strategy results in bleed operation for only about 610 hours, or 7% of the year, whereas for the earlier studies, the bleed was running 8760 hours per year. For either water table depth, the additional pumping power required by increasing bleed rate is more than offset by the reduction in heat pump energy consumption resulting from the more favorable entering fluid temperatures.

**Other Locations**

The same office building was simulated in four other locations for the purpose of comparing the performance of the SCW and single U-tube vertical closed-loop systems. The same procedures used for design and simulation of the systems in Boston were employed for these locations. Those cities were chosen in geological regions that appear to have suitable hydrogeological conditions for SCW systems (Spitler et al. 2002).
Naturally, for any actual SCW installation, the local hydrogeology should be checked. Sachs and Rafferty (2002) discuss water chemistry, dissolved solids, and other environmental issues related to SCW systems. Table 8 gives the far-field temperature and annual building loads for the different cities.

The combination of low far-field temperatures and high heating loads in Concord meant that the minimum design entering fluid temperature of 7°C (44.6°F) could not be met, even with a SCW depth of 1500 m (4922 ft). Therefore, the design temperature was lowered to 5°C (41°F), effectively eliminating the safety margin.

However, a mitigating factor should be noted here. The far-field mean temperatures listed in Table 6 are taken from well water measurements, with depths typically less than 100 m (328.1 ft). For design and simulation of U-tube closed-loop ground heat exchangers, for which the depth seldom exceeds 100 m (328.1 ft), this should be sufficiently accurate. However, for SCW systems with wells exceeding 600 m (1970 ft) in depth, the increase in temperature will likely become significant. Typical ranges for natural geothermal gradients are 0.3°C–1.8°C/100 m (0.2°F–1.0°F/100 ft). For the office building in Concord, the actual far-field temperature, averaged over the well depth, is probably at least 2°C (3.6°F) higher than the far-field temperature used in the simulation. This will benefit SCW systems with heating-dominated loads and, conversely, may be detrimental to SCW systems with cooling-dominated loads. Future work should take this into account.

Table 9 and Figure 7 summarize the calculated specific capacity (feet per ton) for different ground heat exchangers for the small office building. The results show that on average, the SCW system without bleed can reduce the required feet per ton by 46.8%, and the system with bleed can reduce the feet per ton by 62.4%. Likewise, total length requirements, as shown in Figure 8, are reduced in the same proportions.

Table 10 and Figure 9 compare the capital costs for SCW systems and closed-loop systems. Compared with the single U-tube closed-loop system, the SCW system without bleed reduces capital costs by at least 31.5%. With bleed, capital costs are reduced by at least 53.6%.

Table 11 and Figure 10 present the results for 20-year life-cycle cost analysis for different ground heat exchanger systems in different cities. Compared with the single U-tube closed-loop system, the SCW systems without bleed and with bleed reduce 20-year life-cycle cost by at least 16.7% and 26.5% (Harrisburg), respectively. The operating costs of different systems for the same city are fairly similar, but there are significant differences between the capital costs, which cause the great change in the total life-cycle costs.
Table 9. Feet per Ton for Different Ground Heat Exchangers

<table>
<thead>
<tr>
<th>City</th>
<th>Single U-Tube</th>
<th>SCW Without Bleed</th>
<th>SCW With 10% Deadband Bleed Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concord, NH</td>
<td>164</td>
<td>83</td>
<td>60</td>
</tr>
<tr>
<td>Harrisburg, PA</td>
<td>137</td>
<td>104</td>
<td>69</td>
</tr>
<tr>
<td>Boston, MA</td>
<td>121</td>
<td>72</td>
<td>48</td>
</tr>
<tr>
<td>Portland, OR</td>
<td>148</td>
<td>52</td>
<td>33</td>
</tr>
<tr>
<td>Birmingham, AL</td>
<td>135</td>
<td>66</td>
<td>53</td>
</tr>
<tr>
<td>Average</td>
<td>141</td>
<td>75</td>
<td>53</td>
</tr>
</tbody>
</table>

Figure 7 Feet per ton for different ground heat exchangers for a small office building.

Figure 8 Required total borehole depth for different ground heat exchanger systems in different cities.

Figure 9 Capital cost for different ground heat exchanger systems in different cities.

Figure 10 Twenty-year cycle cost (present value) for different ground heat exchanger systems in different cities.

Table 10. Comparisons of Capital Cost for Different Cities*

<table>
<thead>
<tr>
<th>Cities</th>
<th>Single U-Tube</th>
<th>SCW Without Bleed</th>
<th>SCW With Bleed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concord, NH</td>
<td>$23,563</td>
<td>$10,871</td>
<td>$7,992</td>
</tr>
<tr>
<td>Harrisburg, PA</td>
<td>$13,529</td>
<td>$9,262</td>
<td>$6,276</td>
</tr>
<tr>
<td>Boston, MA</td>
<td>$12,866</td>
<td>$6,991</td>
<td>$4,702</td>
</tr>
<tr>
<td>Portland, OR</td>
<td>$13,365</td>
<td>$4,238</td>
<td>$2,700</td>
</tr>
<tr>
<td>Birmingham, AL</td>
<td>$17,467</td>
<td>$7,706</td>
<td>$6,276</td>
</tr>
</tbody>
</table>

* Percentages are the cost reductions compared with single U-tube system.
CONCLUSIONS AND RECOMMENDATIONS

Using simulations, the performance of SCW systems has been examined and compared to the performance of closed-loop GSHP systems. The following conclusions may be drawn from this study. SCW systems allowed significant reductions in borehole depth compared to closed-loop systems. For the building/location combinations in this study, compared with single U-tube vertical closed-loop systems, without bleed, borehole depth reductions between 25% and 65% are possible. With bleed, reductions in the range of 49% to 78% can be achieved. Because of this significant reduction in borehole depth, significant reductions in capital cost and life-cycle cost are possible.

However, this research had a limited scope—it only studied one building type, it used limited data for drilling costs, and it neglected detailed consideration of hydrogeology. Given the significant savings potential, further research is recommended in the following areas.

1. A more careful review of hydrogeology issues such as water chemistry and dissolved solids is warranted. This might be taken in two directions: (1) better identification of locations that are suitable for direct use of SCW water in the heat pumps and (2) for locations where scaling or corrosion are likely to be problematic, it would be worth evaluating SCW systems that use an intermediate heat exchanger, e.g., a plate frame heat exchanger, for isolation of the heat pumps from the SCW water.

2. The economic analysis in this paper relies on drilling costs provided by Yavuzturb and Chiasson (2002). These drilling costs are likely to be highly variable, depending on location. Refinement of drilling and installation cost comparisons through case studies is recommended.

3. Only one building type (a small office building) with one bleed control strategy, was studied. Future work might extend the parametric study to other building types with different load profiles and other bleed control strategies.

4. Standard ground temperature data sources, e.g., IGSHPA (1988), have limitations when used for very deep SCWs. Additional data, especially geothermal gradients, should be incorporated into future studies.

5. The design of both the SCW systems and the closed-loop GSHP systems used fairly simple design procedures, using the fluid temperature at freezing point as the controlling parameter. Both system types have designs with many degrees of freedom, and it would be useful to study alternative design procedures, including optimal design strategies.

ACKNOWLEDGMENTS

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NOMENCLATURE

\[ C = \text{the array of curve-fit coefficients} \]

\[ EFT = \text{the entering fluid temperature to the heat pump, } °C (°F) \]

\[ HP_{\text{capacity}} = \text{the heat pump capacity, W (Btu/h)} \]

\[ HP_{\text{power}} = \text{the power consumption of the heat pump, W} \]

\[ ΔT = \text{the fluid temperature change across the heat pump, } °C (°F) \]

REFERENCES


