Modeling of Standing Column Wells in Ground Source Heat Pump Systems

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1. INTRODUCTION

In recent years, ground source heat pump systems have become increasingly popular for use in residential and commercial buildings. These systems include several different variations, all of which reject heat and/or extract heat from the sub-surface environment:

- Ground-coupled heat pump (GCHP) systems (Closed-loop)
- Surface water heat pump (SWHP) systems
- Groundwater heat pump (GWHP) systems:
    - -- Standing column well (SCW) systems, which utilize a single well for both extraction and injection of groundwater.
    - -- Open loop groundwater systems with separate extraction and injection wells or single extraction well.

Considerable research effort has been spent on the first three systems, especially on the single U-tube ground heat exchanger, in recent decades. Existing engineering design manuals, such as IGSHPA (1988), ASHRAE (1995), Kavanaugh and Rafferty (1997), cover the first three system types. However, relatively few design tools and simulation models are available for SCW systems (Yuill and Mikler 1995; Spitler et al. 2002; Rees et al. 2004; Deng 2004; Deng et al. 2005). Standing column wells have been in use in limited numbers since the advent of geothermal heat pump systems and are recently receiving much more attention because of their improved overall performance in regions with suitable hydrological and geological conditions (Orio 1994, 1995, 1999; Yuill and Mikler 1995; Spitler et al. 2002; Orio et al. 2005).

Groundwater heat pump systems that use groundwater drawn from wells in a semi-open loop arrangement 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. Water is circulated from the well through the heat pump in an open loop pipe circuit. The SCW system can be thought of as a cross between a closed-loop earth-coupled system and an open-loop groundwater source system. During much of the year, they operate by recirculating water between the well and the heat pump. However, during peak temperature periods, they can "bleed" some water from the system to induce groundwater flow. This causes groundwater 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. A typical schematic of a standing column well is shown in Figure 1.

Compared with other ground heat source heat pump 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 temperature and higher heating loads than other areas, so, at this time, most SCW designs are focused on heat extraction.

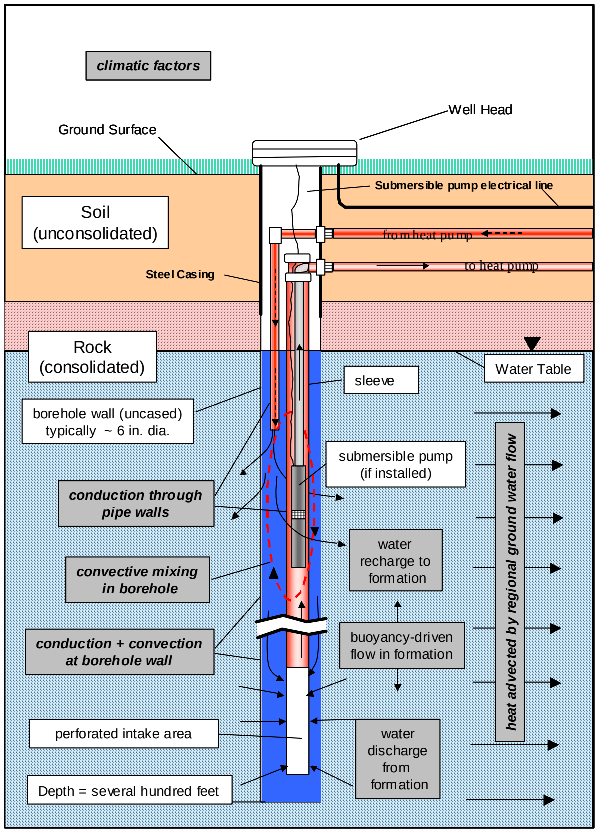

Figure 1 A schematic of a typical standing column well (http://www.hvac.okstate.edu/)

2. MODELS

Conventional closed-loop heat exchangers in geothermal heat pump applications are often modeled assuming pure heat conduction with no heat transfer due to groundwater movement through the surrounding soil/rock. In a standing column well, the fluid flow in the borehole due to the pumping induces a recirculating flow in the surrounding rock. The groundwater flow is beneficial to the SCW heat exchange as it introduces a further mode of heat transfer with the surroundings – namely advection. In addition to the conduction of heat through both the rock and the water, convection heat transfer occurs at the surfaces of the pipework and at the borehole wall. As the borehole wall is porous, fluid is able to flow from the borehole wall into and out of the rock's porous matrix. The magnitude of this flow is dependent on the pressure gradient along the borehole and the relative resistance to flow along the borehole compared to the resistance to flow through the rock. If the dip tube is arranged to draw fluid from the bottom of the well, groundwater will be induced to flow into the rock in the top part of the borehole, and will be drawn into the borehole lower down. At some distance down the borehole there will be a balance point (no net head gradient) at which there will be no flow either into or out of the rock.

A detailed two-dimensional (radial/axial) numerical model of the ground-water flow and heat transfer both within the well and in the surrounding rock has been developed. This has been used to calculate the performance of standing column well systems over yearly periods of operation. A parametric study has been performed to establish the most significant design parameters. Performance has been assessed in terms of heat transfer rates, effective well depth, energy consumption, and costs. The most significant parameters were found to be well depth, rock thermal/hydraulic conductivity, and bleed rate. This work was undertaken as part of ASHRAE 1119-RP and reported by Spitler et al. (2002), Rees et al. (2004), and Deng (2004). The detailed two-dimensional numerical model is composed of two coupled components:

- Thermal energy transport within the well is calculated using a nodal model of the borehole components.

- Flow equations in both the borehole and the surrounding rock, and thermal energy transport in the surrounding rock are calculated using a two-dimensional finite volume model.

This model solves the coupled groundwater flow and heat transfer equations in a domain extending from the borehole to a radius of 180m. Spatial resolution of the head and temperature fields on a small scale near the borehole and extending to the far field requires a large computational mesh (of the order 10,000 cells). This, and the fact that the coupling of the models demands many iterations before convergence is possible, makes the computational overhead excessive when annual hourly simulation or design calculation is attempted.

Accordingly, practical simulation and design calculations require a computationally efficient model of the standing column well. A simplified one-dimensional model was developed for these purposes (Deng 2004; Deng et al. 2005). The simplified one-dimensional numerical model simulates groundwater flow and heat transfer in and around the standing column well. Both the groundwater flow that is 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 pumping (without bleed) 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 sub-models:

- 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): 1) Physical *in situ* test; 2) Numerical *in situ* experiment; 3) Correlations for enhanced thermal conductivity.

3. EXPERIMENTAL VALIDATION

Detailed experimental validation of the models is highly desirable; however, little data are available from experiments or installed SCW systems. Two data sets from existing standing column well systems have been identified. This paper presents a comparison of model results with these two data sets. As not all physical parameters are known for each of the data sets, it was necessary to estimate several parameters, including the rock thermal conductivity and hydraulic conductivity.

Validation with Data from SCW System without Bleed

Mikler (1993) performed experimental studies of transient heat and mass transfer in one standing column well system installed at Pennsylvania State University. The standing column well was in non-bleed operation during the whole experimental period. The undisturbed ground temperature is 10.05°C (50.9°F) at the top of the well, and the ground temperature gradient is 0.6°C/100 m (Mikler 1993). The thermal conductivity of the aquifer could, ideally, be determined from measured data, the drill log, and basic knowledge about the local geology. However, Mikler (1993) took the value of thermal conductivity from tabulated data in a thesis (Hellström 1991). This value was not measured by an in situ test, so it does not necessarily represent actual site conditions accurately. However, by using the experimental data from the first 50 hours of operation, a parameter estimation procedure can be applied to estimate the enhanced thermal conductivity in the same way as with measurements taken during an in situ test. The enhanced thermal conductivity was estimated to be 3.80 W/(m·K) [2.19 Btu/hr-ft-°F] (Deng 2004).

Comparisons of the well outlet temperatures in both cooling and heating modes from the models and Mikler's data are shown in Figure 2. The root mean square differences, between the temperatures at the outlet to the well measured by Mikler and those predicated by the simplified and detailed models are 0.8°C and 0.5°C respectively. This validation exercise demonstrates that both models can be used to adequately simulate standing column well systems in non-bleed operation. Likely reasons for the difference between temperatures predicted by the models and temperatures from measurements are:

• In reality, it is likely that there are some rock fractures near the well so that the aquifer surrounding the well is not perfectly homogenous or isotropic as assumed by the models.

• The thermal and hydrogeological properties of the surrounding rock used in this validation such as thermal conductivity and hydraulic conductivity were not measured with in situ tests, and the values utilized have an unknown amount of uncertainty.

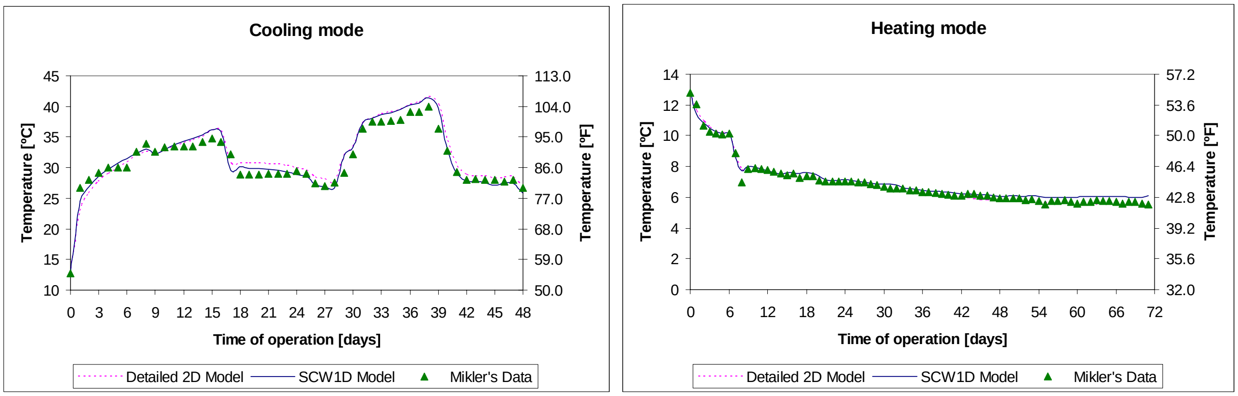

Figure 2 Comparisons of temperatures at the outlet to the well for the detailed model 2D model, simplified model (SCW1D), and Mikler's data in cooling and heating mode

Validation with Data from a SCW System with Bleed

The bleed mode of operation, which has a significant impact on the SCW system, was not investigated in Mikler's experiment. In order to validate the bleed operation of the model, a data set from a SCW system at the Haverhill, Massachusetts, public library was used (Henderson 2003). Deng (2004) and Deng et al. (2005) described this validation in detail.

Figure 3 shows that, using the Haverhill Public Library data, there is good agreement between measured and calculated well outlet temperatures. As noted earlier, these differences are thought to be due to the assumptions of there being a homogenous and isotropic aquifer, use of an estimated thermal conductivity, neglect of ground temperature gradient, vertical heat and fluid flow (for SCW1D model). These differences are smaller than those found using Mikler's data (Mikler 1993). This improvement appears to come from increased measurement frequency. Mikler's data are given as daily average values; the data from the Haverhill library are hourly instantaneous values. The differences found in this validation exercise are acceptably small and show that the model can also be used to adequately simulate the standing column well systems in bleed operation.

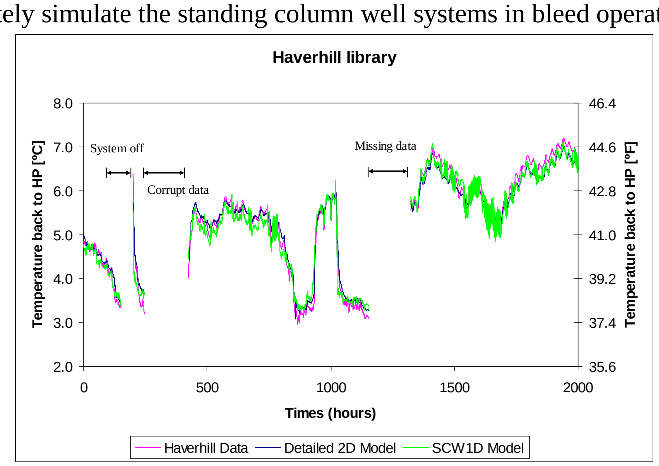

Figure 3 A comparison of calculated and measured temperatures at the outlet of the well using the Haverhill Public Library installation data

4. APPLICATION EXAMPLE

In this section, simulation results for a real building using different ground heat exchanger systems (i.e., single u-tube closed-loop system, standing column well system without bleed, and standing column well system with bleed) are described. Deng (2004) and Deng et al. (2006) gave the detailed descriptions of simulation environment assumptions, and procedures.

The single u-tube closed loop ground heat exchanger model used in this study is that developed by Yavuzturk and Spitler (1999), where the short-time step g-functions were used. The standing column well heat exchanger model used in this study is the simplified model (Deng 2004; Deng et al. 2005). Both models are run in the HVACSIM+ environment (Clark 1985). All the simulations are made using building loads calculated for a building (the Meridian Technology Center Incubator) located in Stillwater, OK with a Boston, MA, weather file (Figure 4). The building loads are determined using building energy simulation software (BLAST 1986). This building has previously been used in other energy studies (Yavuzturk 1999).

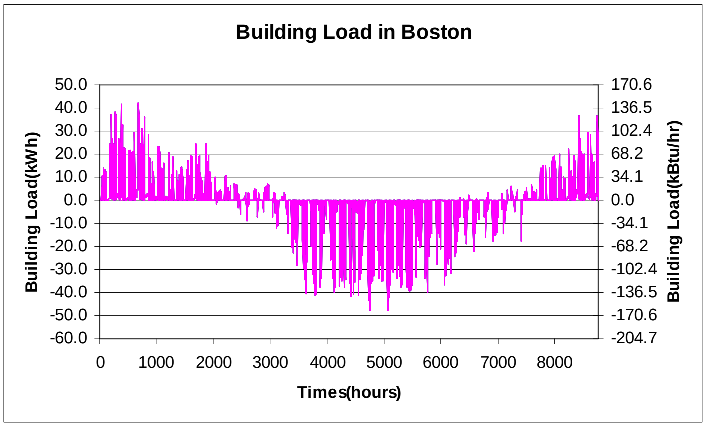

Figure 4 Building load of a building in Boston (Positive loads are heating load)

The ground heat exchanger design parameters used in this study, including the borehole thermal resistance values for each case, are summarized in Table 1. The ground conditions are assumed to be similar to that in the northeast of the U.S (Northeastern Appalachians Region). These systems have many degrees of freedom in their design. In order to make a fair comparison, each of the ground heat exchangers was sized to have a minimum entering water temperature of about 5.6ºC (42.1ºF) and maximum entering water temperature of about 25.6ºC(78.1ºF). The closed-loop system uses an antifreeze mixture of 12.9% propylene glycol by weight. In this study, deadband bleed control strategy (Deng 2004) is used during bleed operation. In winter, when exiting water temperature is lower than 8ºC (46.4ºF), bleed is started. When exiting water temperature is higher than 10.8ºC (51.4ºF), bleed is stopped. In summer, bleed is started when exiting water temperature is higher than 29.2ºC (84.5ºF), and stopped when exiting water temperature is lower than 26.4ºC (79.5ºF).

Table 1 Summary of ground heat exchanger design parameters for Boston, MA

Designer Parameter	**Single U-tube closed- loop**	**Standing column well (without bleed)**	**Standing column well (with 10% bleed)**
Geologic Conditions:			
Rock Type	Fractured igneous and metamorphic rock	Fractured igneous and metamorphic rock	Fractured igneous and metamorphic rock
Thermal Conductivity (W/m-K) (Btu/hr-ft-ºF)	3.0 (1.73)	3.5(Enhanced) (2.02)	3.5(Enhanced) (2.02)
Vol. Heat Capacity (J/m^3-ºC) (Btu/ft^3-ºF)	2,600,000 (38.78)	2,600,000 (38.78)	2,600,000 (38.78)
Undisturbed Earth Temperature (ºC) (ºF)	12.2 (53.96)	12.2 (53.96)	12.2 (53.96)
Water Table Depth (m) (ft)	5 (16.41)	5 (16.41)	5 (16.41)
Borehole:			
Diameter (m) (in)	0.11 (4.33)	0.1524 (6)	0.1524 (6)
Depth (m) (ft)	81.68 (268)	391 (1,283)	263 (863)
Borehole Geometry	1 × 8	Not applicable	Not applicable

U-tube (HDPE):			
Diameter inner (m) (in)	0.025 (1)	Not applicable	Not applicable
U-tube Shank Spacing (m) (in)	0.0367 (1.44)	Not applicable	Not applicable
Thermal Conductivity (W/m-K) (Btu/hr-ft-ºF)	0.3895 (0.225)	Not applicable	Not applicable
Grout			
Type	Standard Bentonite	Not applicable	Not applicable
Thermal Conductivity (W/m-K) (Btu/hr-ft-ºF)	0.7443 (0.433)	Not applicable	Not applicable
Borehole Thermal Resistance:			
$R_{borehole}$ (ºC/W/m) (ºF/(Btu/hr)/ft)	0.1398 (0.2419)	0.0011 (0.0019)	0.0011 (0.0019)

In Table 1, the borehole thermal resistance for a single vertical U-tube closed-loop system is calculated from a ground heat exchanger design tool (Spitler 2000), and the borehole thermal resistance for standing column well system is obtained from the methodology described by Deng (2004). The results of the simulation portion of the design procedure are summarized in Table 2. Because all three systems are designed to have the same peak entering fluid temperatures, the hourly temperatures are fairly similar. Daily peak fluid temperatures of the three systems have differences between 0.01 and 0.22ºC (0.02 and 0.4ºF). As can be seen here and in Figure 5, the SCW system requires significantly less borehole/well depth than a standard closed-loop system design. Compared with the single U-tube closed-loop system, the standing column well system without bleed reduces the required depth by 40%, and the system with bleed reduces the required depth by 60%. 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 standing column well system can therefore significantly reduce the capital costs, particularly drilling costs, compared to a closed-loop system.

Table 2 Summary of ground heat exchanger design results for Boston weather file

Ground Heat Exchanger Type	Borehole Geometry	Borehole Depth (m) [ft]	Required Total Borehole Length (m) [ft]	EFT_{max} (ºC) [ºF]	EFT_{min} (ºC) (ºF)	Feet per ton
Single U-tube closed- loop	1 × 8	82 (268)	653 (2,144)	29.7 (85.5)	3.4 (38.2)	121
Standing Column Well Without Bleed	1 × 1	391 (1,283)	391 (1,283)	22.8 (73.1)	7.0 (44.6)	72
Standing Column Well With 10% Bleed (Deadband Control)	1 × 1	263 (863)	263 (863)	28.1 (82.5)	7.0 (44.6)	48

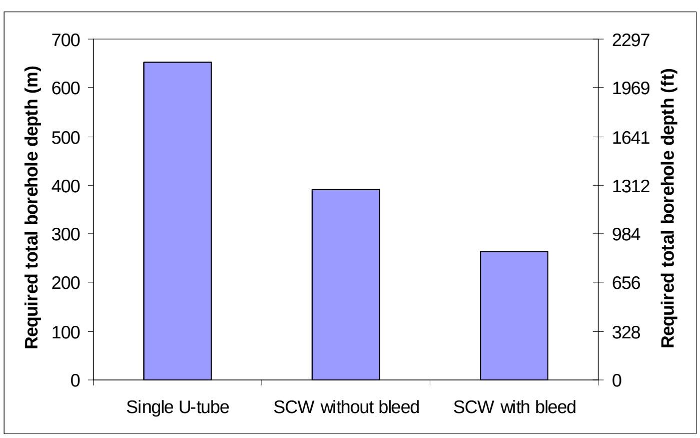

Figure 5 Required total borehole/well depth for different ground heat exchanger systems in Boston, MA

Figure 6 shows preliminary 20-year life cycle cost analyses for different ground heat exchanger systems in Boston, MA. The net present value is based on the cost assumptions from Yavuzturk and Chiasson (2002). Because the systems have been designed to have similar entering fluid temperatures, the operating costs are fairly similar. The capital costs are significantly different, though. It should be noticed that the circulating water pump costs for SCW system are greatly dependent on the water table depth. In this preliminary study, the water table is high (i.e., 5 meters), so the circulating water pump cost difference between SCW systems with bleed and without bleed is very small. If the water table is lower, for higher rates of bleed, the circulating water pump costs could be higher (Rees et al. 2004). The same study also shows that for constant and continuous bleed operation, when the water table is low, on the order of 30 meters (98 ft), the benefits of higher rates of bleed (> 10% in the study by Deng [2004]) are outweighed by the increased pumping costs. The detailed performance analyses of these systems in different areas with different water table depths, including energy consumption and life cost were reported by Deng (2004) and Deng et al. (2006).

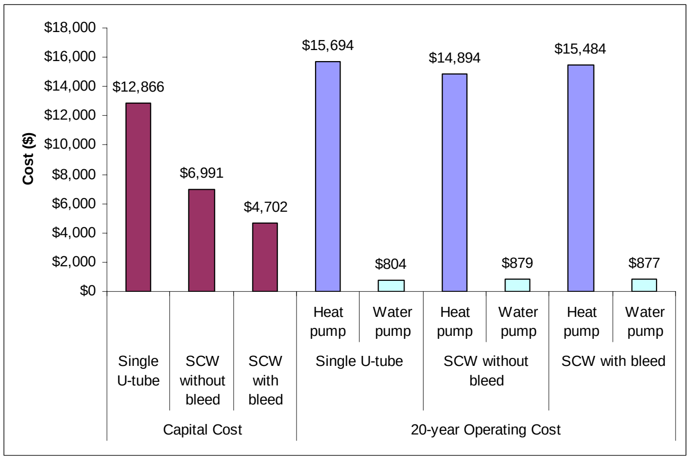

Figure 6 20-year life cycle cost (present value) in Boston, MA

5. CONCLUSIONS AND RECOMMENDATIONS

This paper simply introduces a detailed two-dimensional finite volume model and simplified one-dimensional finite difference model for standing column well systems with the consideration of groundwater movement in the surrounding rock. The simplified model is efficient for either annual hourly energy analysis programs or standing column well design programs. Both models have been validated against experimental data. An important limitation of these two available data sets is that no *in situ* measurements of the rock thermal and hydraulic conductivities were made and these values therefore were estimated from the first portion of the experimental data sets.

Using simulation, the performance of standing column well 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 office building in Boston, compared with single vertical U-tube closed-loop systems, without bleed, borehole depth is reduced by 40%. With bleed, reduction of 60% can be achieved. Because of this significant reduction in borehole depth, significant reductions in capital cost and life cycle cost are possible. However, the study had a limited scope-- it only looked at one building type, used limited data for drilling costs, and neglected detailed consideration of hydrogeology.

Recommendations for future research include the following:

- Develop a model to simulate multiple standing column wells with thermal interaction.
- As discussed above, the existing experimental data sets utilized in this paper had several limitations that should be rectified in future experimental work. Specifically, *in situ* measurements of thermal conductivity and hydraulic conductivity should be made; and the instrumentation and measurements should be carefully monitored throughout the experiment so as to obtain a lengthy data set, free of missing and corrupted data.
- Future research might extend the investigation to combined heat and mass transfer in the fractures surrounding the standing column well.
- Use of standard ground temperature data sources, e.g. IGSHPA (1988), has limitations when used for very deep standing column wells. Additional data, especially geothermal gradients, should be incorporated into future studies.

6. ACKNOWLEDGMENTS

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