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A Model for Annual Simulation of Standing Column Well Ground Heat Exchangers

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Standing column wells can be used as highly efficient ground heat exchangers in geothermal heat pump systems. This paper describes a computationally efficient numerical model of groundwater flow and heat transfer in and around standing column wells. An approach that utilizes an "enhanced" thermal conductivity to account for the natural groundwater movement, but which explicitly models the induced groundwater flow by "bleed," is proposed. This model has been validated with experimental data and a reference numerical model (Spitler et al. 2002; Rees et al. 2004; Deng 2004). This simplified model is intended for use in hourly simulation programs or design tools.

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 ground.

- 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 ground-source heat pump systems, especially on the single U-tube ground heat exchanger, in recent decades. Existing engineering design manuals, such as IGSHPA (1988), ASHRAE (1995), and Kavanaugh and Rafferty (1997), cover the first two system types and open-loop groundwater systems. 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). Standing column wells have been in use in limited numbers since the advent of geothermal heat pump systems but 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; Rees et al. 2004; Deng 2004).

Groundwater heat pump systems that use groundwater drawn from and returned to the same well in a semi-open-loop arrangement are commonly known as standing column well (SCW)

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systems. The ground heat exchanger in such systems consists of a vertical borehole 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 and returned to the same well. During much of the year, the system operates by recirculating water between the well and the heat pump. However, during peak temperature periods, it can "bleed" some water from the system by returning only part of the flow to the well and discharging the remainder. This induces groundwater flow from the surrounding formation into the well. This cools the well and surrounding ground during heat rejection in the summer and heats the well and surrounding ground during heat extraction in the winter. By controlling the amount of bleed, fluctuations in the well temperature can be reduced and high system efficiency maintained. A diagram of a typical standing column well is shown in Figure 1.

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

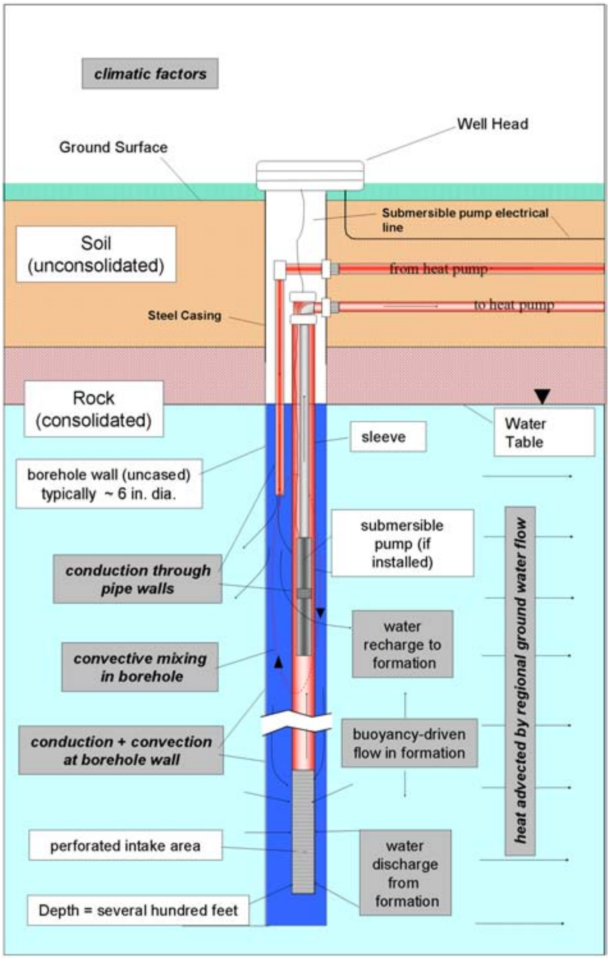

Figure 1. A schematic of a typical standing column well (Spitler et al. 2002).

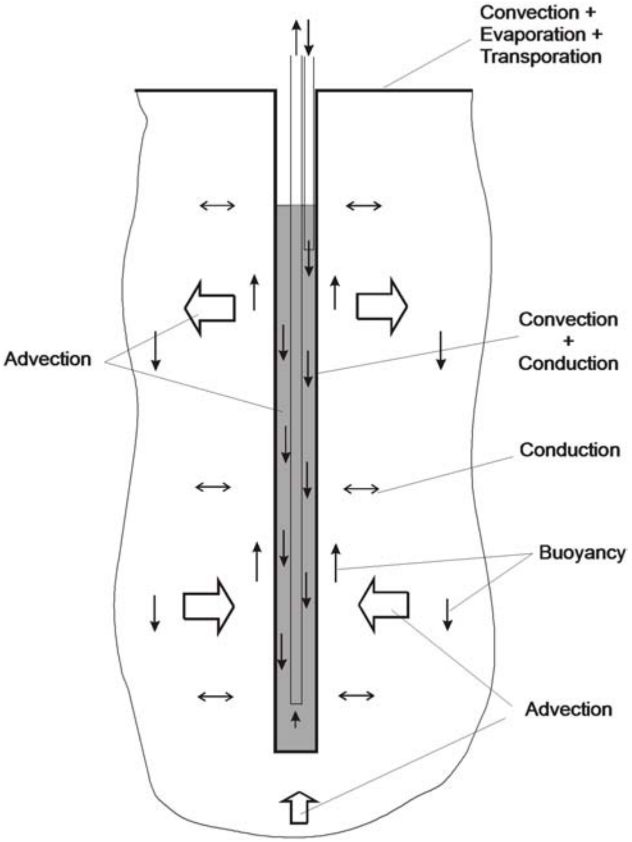

Figure 2. A diagram showing the different modes of heat transfer in and around a standing column well.

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. The heat transfer processes in and around a standing column well are illustrated in Figure 2.

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 groundwater 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 RP-1119 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 180 m. 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 (in 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. This detailed two-dimensional model has been used in this work as a source of reference data.

Accordingly, practical simulation and design calculations require a computationally efficient model of the standing column well. This paper describes a model developed for these purposes. The model has been validated using experimental data and data from the reference numerical model.

MODEL DEVELOPMENT

Both the natural groundwater movement and the groundwater flow induced by “bleed” are considered in this model. An “enhanced” thermal conductivity is used to consider the natural water flow caused by the pumping and buoyancy. However, bleed-driven advection is represented explicitly. When bleed occurs, its effect is superimposed on top of the effects of pumping and buoyancy. The simplified one-dimensional numerical model to be described has two submodels:

- Thermal and fluid energy transport in the surrounding rock are handled by a one-dimensional (radial) finite difference model, which solves a 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.

In this simplified SCW model, several assumptions are made regarding the domain outside the borehole:

- The aquifer is homogenous and isotropic.
- Density dependent flow is neglected.
- There is no vertical heat or water flow.
- There is zero natural ground temperature gradient.

The first assumption, that the aquifer is homogenous and isotropic, is necessary to achieve reasonable computational speed for design and simulation purposes. It is also appropriate for these uses—detailed knowledge of fracture geometry is rarely available to system designs. Deng (2004) considered a limiting case for heterogeneous and anisotropic aquifers, where the rock formed an impermeable medium with a large water-bearing facture. For a one-year simulation, the maximum difference in predicted heat pump entering fluid temperature between the limiting case and the isotropic case is 2°C.

The simplified one-dimensional numerical model is described in this section. First, the governing energy equation in the surrounding rock is given, and then borehole heat transfer including that between the tubes is analyzed. Second, the simplified model with enhanced thermal conductivity is discussed. Finally, the simplified model is validated by comparison with the detailed model (Spitler et al. 2002; Rees et al. 2004; Deng 2004).

Groundwater Heat Transfer

Assuming that the vertical heat and water flow can be neglected in standing column well systems for both non-bleed and bleed cases, the one-dimensional energy equation (in the radial direction) in a porous medium can be written as

$$\alpha\frac{\partial T}{\partial t}+\beta V_r\frac{\partial T}{\partial r} = \Gamma\left[\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}\right]. \tag{1}$$

α, β, and Γ are determined from the water and rock thermal properties

$$\alpha = n\rho_l C_{pl}+(1-n)\rho_s C_{ps} \tag{2}$$

$$\beta = \rho_l C_{pl} \tag{3}$$

$$\Gamma = k_{eff} = nk_l+(1-n)k_s. \tag{4}$$

In this one-dimensional model, the average groundwater velocity, V_r, at radius r_i is not determined by explicitly solving a partial differential equation to find the head gradient (Darcy's law), as it is in the reference model (Spitler et al. 2002; Rees et al. 2004; Deng 2004). Instead, assuming homogeneous conditions in the surrounding rock and that net flow is toward the borehole during bleed, as indicated in Figure 3, conservation of mass may be used to calculate this velocity in bleed cases.

$$V_{ri} = -\frac{1}{n}\frac{\dot{m}b}{\rho_l A} = -\frac{1}{n}\frac{\dot{m}b}{\rho_l}\frac{1}{2\pi r_i L} \tag{5}$$

As this is a one-dimensional simplified model, the influence of the hydraulic conductivity cannot directly be taken into account. It is assumed that the well drawdown (depression of the water table at the top of the well due to pumped extraction) is small compared to total borehole depth, and its effect on heat transfer can be neglected. This assumption is reasonable for a typical standing column well where the depth is often more than 300 m (Deng 2004).

To solve the given partial differential equation (Equation 1), boundary conditions are established as follows:

- A constant temperature, T_{far}, is set at the far field, R_∞. The value of R_∞ can be taken from a sensitivity analysis of domain radius for ten-year simulation and set here as 65 m.

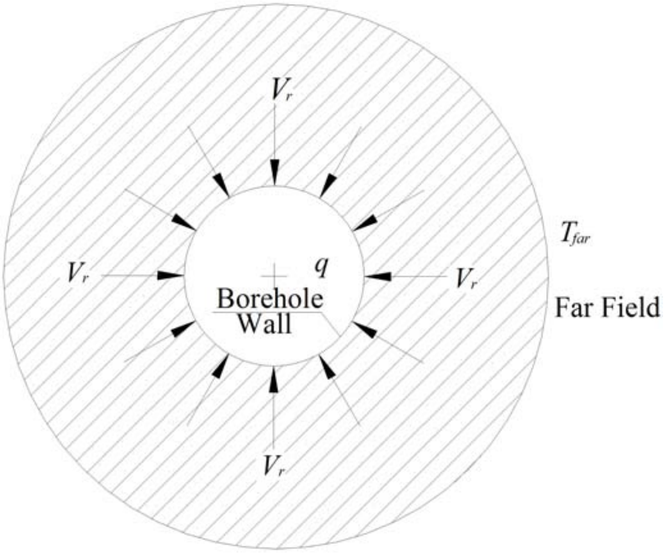

Figure 3. Schematic drawing showing a one-dimensional model for the SCW system (with given boundary conditions).

- A heat flux q (W/m^2) is set at the borehole wall according to the current value of the temperature gradient between the fluid and wall using the borehole resistance so that

$$q = \frac{T_b - T_f}{R_b} \cdot \frac{1}{2\pi r_b} . \tag{6}$$

Figure 4 shows a schematic of the one-dimensional model of the standing column well. There is a heat flux applied to the borehole wall per unit area of the borehole wall. The solution to Equation 1 for the surrounding rock (the shaded region in Figure 3) is used to find the borehole wall temperature. This, in turn, is used in Equation 6 to find the borehole wall heat flux. The partial differential equation (Equation 1) can be solved numerically using the given boundary conditions. In this study, a fully implicit finite difference method (FDM) is used. The solution of the discrete equations for this one-dimensional problem is obtained by applying the tri-diagonal matrix algorithm.

Borehole Heat Transfer

The conceptual model of the borehole fluid flow and heat transfer is illustrated in Figure 4. The fluid in the well and surrounding the dip tube is assumed to be well mixed. The temperature of this fluid is approximated by the arithmetic mean value of the entering and exiting system water temperatures T_{fo} and T_{fi}. (This approximation is commonly used in the simulation and design of U-tube ground heat exchangers.) After considering the proportion of system fluid bled from the system (b), the average water temperature in the standing column well, T_f, is given as

$$T_f = \frac{(1-r)T_{fi} + bT_{gw} + T_{fo}}{2} . \tag{7}$$

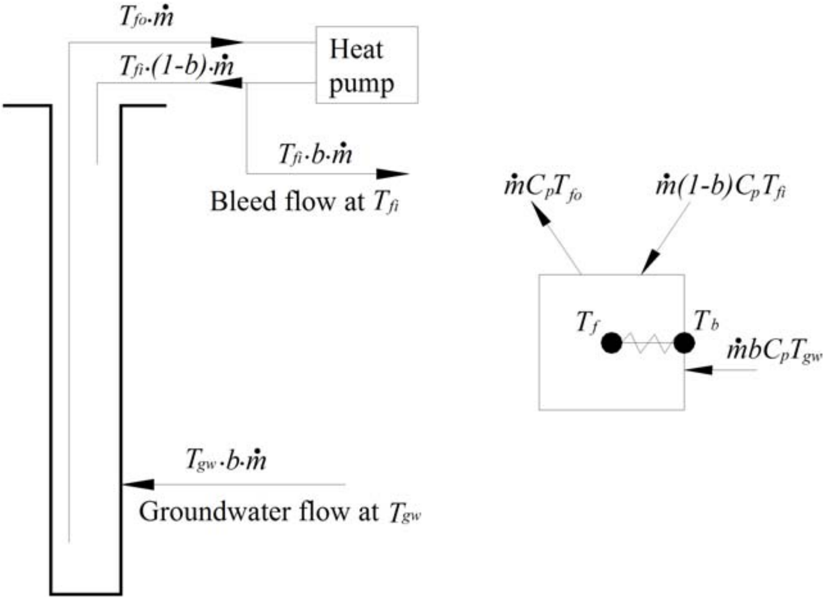

Figure 4. The simplified thermal borehole model.

Rearranging Equation 7,

$$T_{fo} = 2T_f - (1-b)T_{fi} - bT_{gw} . \tag{8}$$

The energy balance can be formulated for the borehole, assuming that the water in the borehole is well mixed and there is only one node in the borehole, where the lump includes water inside the dip tube (Figure 4). The short-circuiting heat transfer due to temperature difference between the water flowing up in the dip tube and the water flowing down in the annulus will be considered later.

$$MC_p\frac{dT_f}{dt} = \dot{m}(1-b)C_pT_{fi} + \dot{m}bC_pT_{gw} - \dot{m}C_pT_{fo} + \frac{T_b - T_f}{R_b}\cdot L \tag{9}$$

Equation 9 states that the net energy entering the well by advection plus the energy entering the well by convection from the borehole wall equals the time rate of change of thermal energy within the well.

As noted above, the assumption is made that the surrounding rock is homogenous, which means that groundwater enters the well at the borehole wall temperature (i.e., $T_{gw} = T_b$). Substituting Equation 8 into Equation 9 and rearranging gives

$$MC_p\frac{dT_f}{dt} = 2\dot{m}(1-b)C_pT_{fi} + 2\dot{m}bC_pT_b - 2\dot{m}C_pT_f + \frac{T_b - T_f}{R_b}\cdot L . \tag{10}$$

Solving the discrete version of this equation gives the average water temperature T_f. The two components of the model are coupled by using the fluid temperature T_f calculated using the borehole nodal model to define the flux boundary condition for the finite difference model of the ground (Equation 6). The finite difference calculation is used to obtain a revised value of the borehole wall temperature T_b. The solution is reached by a process of successive substitution.

Suction Tube Heat Transfer

The configuration of pipes in a standing column well introduces a complication, as there is heat transfer within the standing column well due to temperature differences between the water flowing up in the dip tube (suction pipe) and the water flowing down in the annulus. This temperature difference is greatest at the top of the well, and the resulting heat transfer through the pipe wall is detrimental to standing column well system efficiency. Figure 5 shows typical borehole temperature variation along the borehole depth in heating mode (Spitler et al. 2002; Deng 2004).

To address this phenomenon in the standing column well, the model makes a correction to the water temperature leaving the well (returning to the heat pump), T_{fo}. This heat flux is calculated by an integral method, where the short-circuiting effect is considered in a general heat transfer equation from an element of differential depth (Appendix A). This equation is integrated over the entire length of the borehole.

Enhanced Thermal Conductivity

Three different effects on the heat transfer in standing column well systems may be differentiated:

- Water filling the pores of otherwise dry rock increases the thermal conductivity from the value associated with dry rock. This increased thermal conductivity is referred to as "effective thermal conductivity" k_{eff} (Equation 4).
- The recirculation of water in and out of the well and buoyancy forces drive some water flow in the surrounding rock. With this natural water flow, the advection heat transfer augments the conductive heat transfer. Although heat transfer under groundwater flow conditions is an

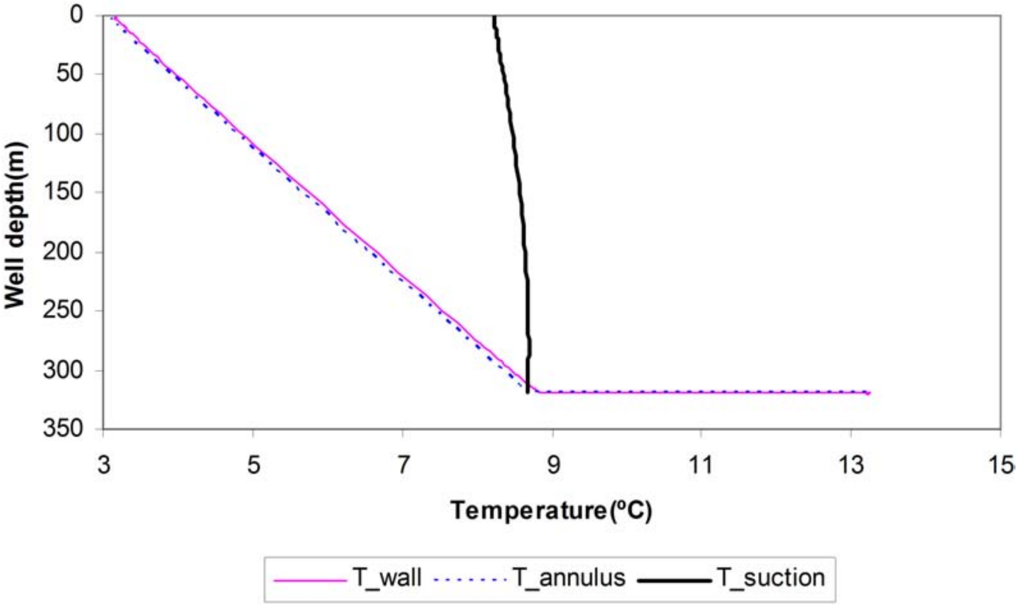

Figure 5. Typical borehole temperature variation along the well depth.

advection-conduction problem, it is possible to treat it as pure conduction by using “enhanced thermal conductivity.” This is the value of thermal conductivity that, in a pure conduction analysis, approximates the heat transfer rate in the convection-diffusion process.

- When bleed occurs, the advection effects can become quite significant and it is no longer feasible to treat the process as a pure-conduction process with an increased thermal conductivity (Deng 2004). Therefore, the model represents bleed-driven advection explicitly, but simply, by assuming it is one-dimensional and the water moves only in the inward direction (indicated in Figure 3).

Equation 5, utilized by the simplified one-dimensional numerical model necessitates that, when the bleed rate is zero, the advection term in the energy equation will be reduced to zero. However, since we still wish to account for the increased heat transfer due to pumping and buoyancy effects, the simplified model uses enhanced thermal conductivity. Then, when bleed occurs, the effect of bleed is superimposed on top of the effects of pumping and buoyancy.

It is thus necessary to estimate the enhanced thermal conductivity. The physical in situ test (Austin et al. 2000) is one way to estimate the actual enhanced thermal conductivity. The temperature response to a pulse heat input, typically of 50 hours duration (Austin et al. 2000), is inversely analyzed to estimate the thermal conductivity. The analysis assumes only conduction, so the estimated value under conditions with groundwater flow is the enhanced thermal conductivity. If an in situ test of thermal conductivity is performed, the measured thermal conductivity at the well site under the influence of groundwater movement may be estimated and used directly in the simplified model. Two alternative approaches involving use of the detailed two-dimensional numerical model are presented by Deng (2004).

Validation Against the Detailed Numerical Model

The model described here, with enhanced thermal conductivity, has been first validated using data from the reference numerical model developed in ASHRAE RP-1119 (Spitler et al. 2002; Rees et al. 2004; Deng 2004). A set of annual simulations has been made by using one year’s worth of hourly building loads as thermal boundary conditions. The building loads are determined by using building energy simulation software (BLAST 1986). The building types selected for this study are an office, a school, and a motel. The building loads have been calculated for three locations (Boston, MA; Tulsa, OK; and Houston, TX) with typical meteorological weather data. Further details of the buildings, systems, and loads are given by Deng (2004), Yavuzturk and Spitler (2000), and Chen (1996).

The design data for the well follow that given by Mikler (1993). The parameters used in the simulation are given in Tables 1 and 2. This well has a dip tube (suction tube) extending to very near the bottom of the well, and the discharge from the heat pump system is near the top. The ground conditions are assumed to be similar to those in the northeast of the United States.

In total, 37 different cases with bleed rates between 0% and 30%, borehole diameters of 140 and 152 mm, borehole depths of 240 and 320 m, and thermal/hydraulic conductivities shown in Table 3 have been analyzed.

The enhanced thermal conductivities for these cases are obtained by one of the alternative approaches described by Deng (2004), a numerical analog to an in situ test. Using the detailed reference model, the response to a pulse heat input of 50 hours duration is obtained. The enhanced thermal conductivity is estimated by inversely analyzing the temperature response with a conduction-only model (Deng 2004). The resulting enhanced thermal conductivities are summarized in Table 3. Then the enhanced thermal conductivities are used in the one-dimensional numerical model to perform a one-year simulation with hourly time steps. The maximum and minimum water temperatures leaving the well (back to the heat pump) for the year, calculated by

Table 1. Hydraulic and Thermal Properties of the Rock (Karst Limestone)

Hydraulic Properties		
Hydraulic Conductivity (*K*) m/s	**Porosity (*n*) (---)**	**Specific Storage (S_s) m^{-1}**
1.0E-05 -- 1.0E-03	0.275	1.00E-05
Thermal Properties		
Thermal Conductivity (*k*) W/(m·K)	**Density (ρ) kg/m^3**	**Specific Heat (C_p) J/(kg·K)**
Enhanced thermal conductivity will be used 2.41 -- 5.36	2700	1000

Table 2. Properties of the Borehole

Parameter	**Depth m**	**Diameter mm**	**Wall Thickness mm**	**Thermal Conductivity W/(m·K)**	**Surface Roughness mm**
Borehole	320	152.4	----	----	1.5
Discharge pipe	2	33.4	3.05	4	1.5
Suction pipe	318	101.6	6.35	0.1	1.5

Table 3. Enhanced Thermal Conductivity from a Numerical Analog to an In Situ Test

Hydraulic Conductivity m/s	**Effective Thermal Conductivity ($k_{effective}$) W/(m·K)**	**Enhanced Thermal Conductivity ($k_{enhanced}$) W/(m·K)**
7.0E-05	1.97	2.41
5.0E-04	1.97	2.98
1.0E-03	1.97	3.68
1.0E-05	2.33	2.64
7.0E-05	2.33	2.73
1.0E-04	2.33	2.78
2.5E-04	2.33	3.00
3.5E-05	3.27	3.48
7.0E-05	3.27	3.55
2.5E-04	3.27	3.94
7.0E-05	4.78	5.26
1.0E-04	4.78	5.36

the simplified model, are compared to those calculated by the detailed model. The results are shown in Figures 6 and 7. Points lying along the line show good agreement between these two models. It is important to note the difference in computational resources required to run this model and the reference model. Using a 2.8 GHz Pentium PC, the detailed model took approximately seven days to perform the annual simulation; the simplified model took less than two seconds.

The biggest errors between the detailed model and the simplified model occur for the cases with shallower depth (240 m). This is presumed to be caused by end effects, i.e., conduction around and below the bottom of the well. The model, being effectively one-dimensional, is not able to take account of these effects, whereas the reference model, by representing the end of the borehole explicitly, shows the expected sensitivity to shallower depths.

In a similar way, it is not possible to represent the effect of any vertical ground temperature gradient. The mean surrounding ground temperature is the boundary condition applied. To examine the significance of the effect of vertical temperature gradient, results have been compared with those of the reference model with ground temperature gradients of 0.3°C/100 m, 0.6°C/100 m, and 1.8°C/100 m. Figure 8 compares the minimum exiting water temperatures from the well under these temperature gradients. The results show that ground temperature gradient does cause some difference, particularly when the gradient is large. However, when the gradient is less than 0.6°C/100 m, the difference is less than 0.2°C and can be neglected. It might also be noted that the three cases started with the same near-surface ground temperature, so the three different gradients result in three different average ground temperatures and three different minimum entering water temperatures. For the two experimental locations in Pennsylvania and Massachusetts, discussed below, the ground temperature gradients are 0.6°C and 0.9°C/100 m. These values are believed to be typical for the geological formations in which SCW systems are installed.

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 parameters used in the validation are given in Tables 1 and 2. The undisturbed ground temperature is 10.05°C 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 could 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) (Deng 2004).

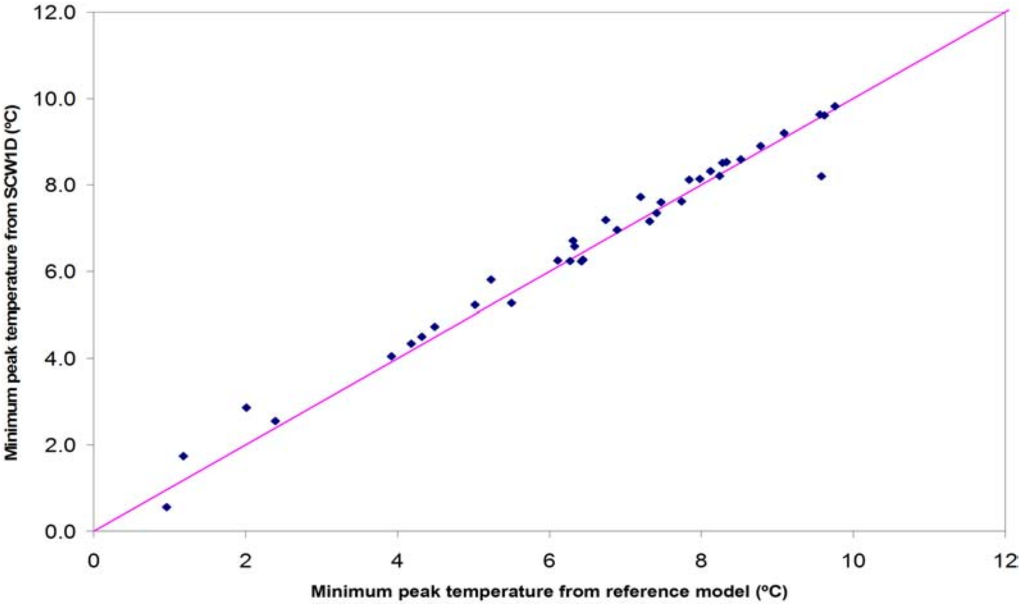

Figure 6. Comparison of minimum temperatures leaving the SCW with data from the reference model.

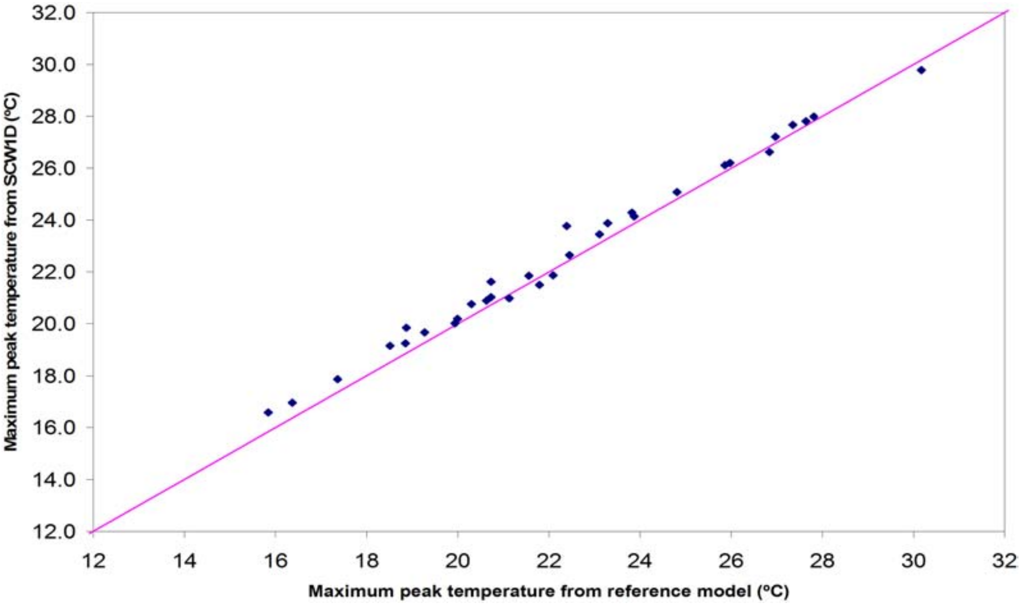

Figure 7. Comparison of maximum temperatures back to the heat pump in different models.

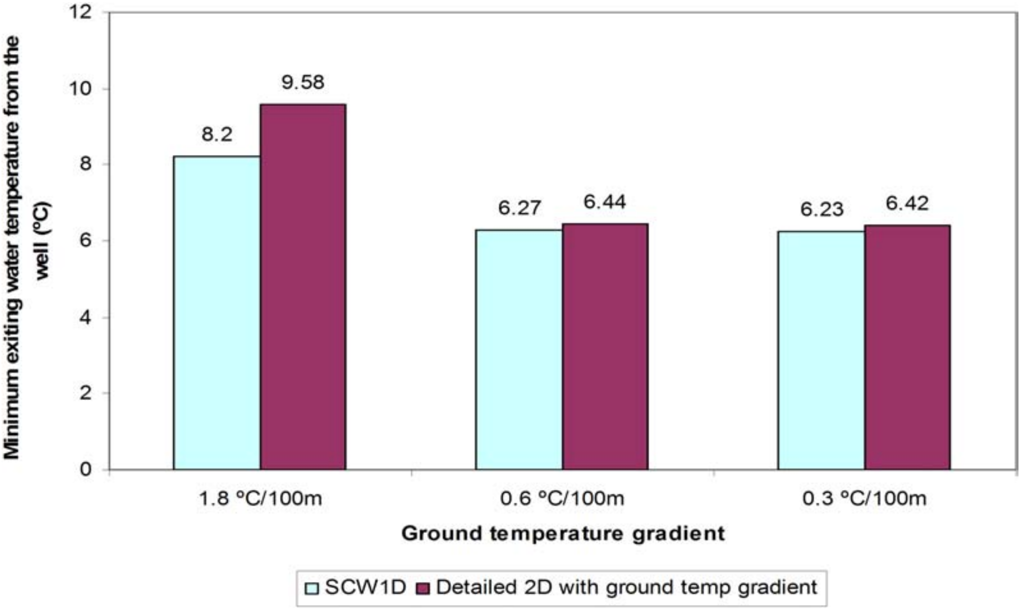

Figure 8. Comparison of the minimum exiting water temperatures from the well in different models with ground temperature gradients.

Comparisons of the temperatures back to the heat pump in both cooling mode and heating mode from the models and Mikler's data are shown in Figures 9 and 10.

Figures 9 and 10 show that there is good agreement between the temperatures at the outlet to the well predicted by the models and Mikler's data. This exercise shows that both models can be used to adequately simulate the standing column well systems in non-bleed operation. The root mean square errors are 0.8°C and 0.5°C for this and the reference model, respectively. The maximum temperature difference between the model and Mikler's data is 1.5°C. 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 model.
- 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.

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). The measured hourly data include:

- Total power use of the heat pumps
- Total power use of the well pumps
- Outdoor air temperature
- Water temperatures entering and leaving the wells

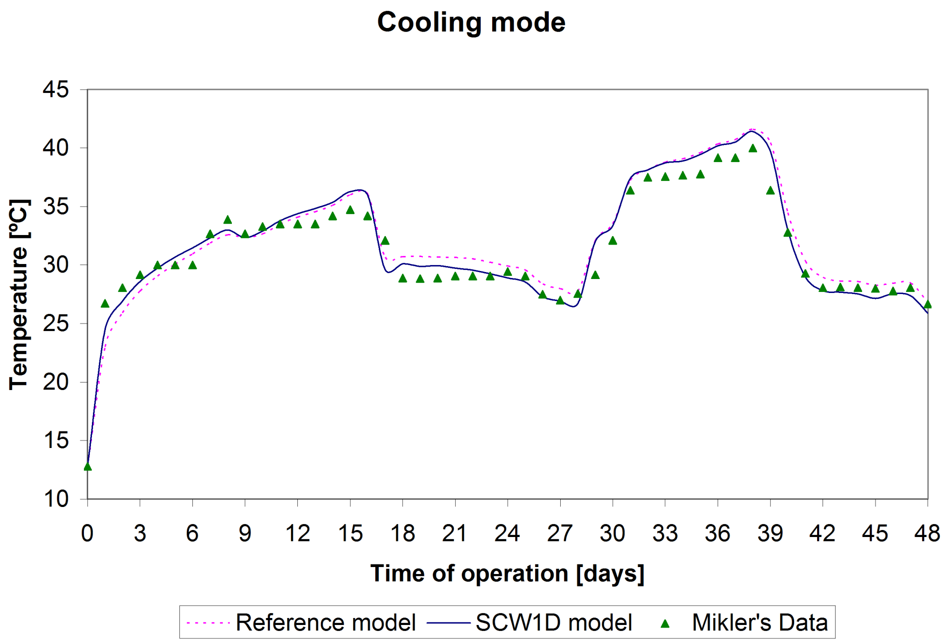

Figure 9. Comparisons of temperatures at the outlet to the well for the simplified model (SCW1D), reference model, and Mikler's data in cooling mode.

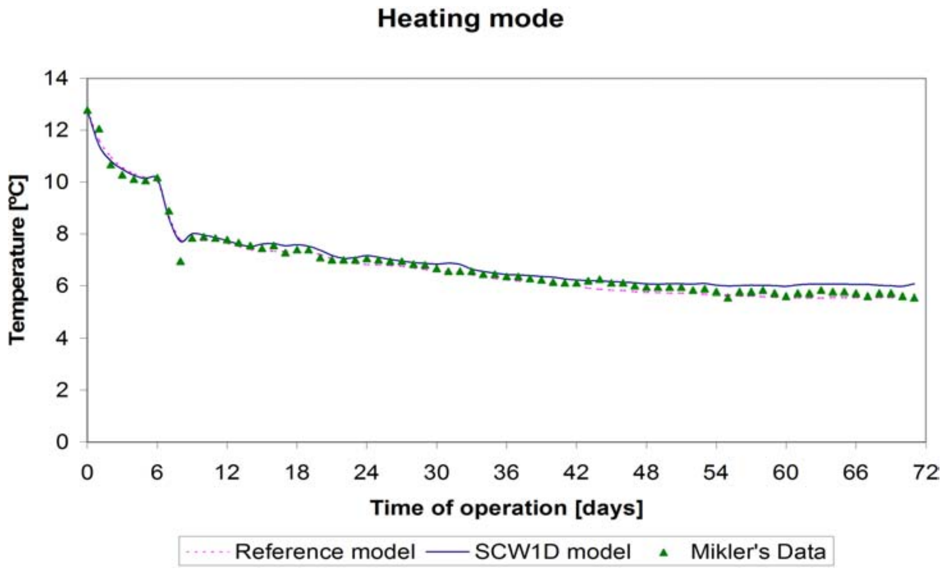

Figure 10. Comparisons of temperatures at the outlet of the well in heating mode for the simplified model (SCW1D), reference model, and Mikler's data in heating mode.

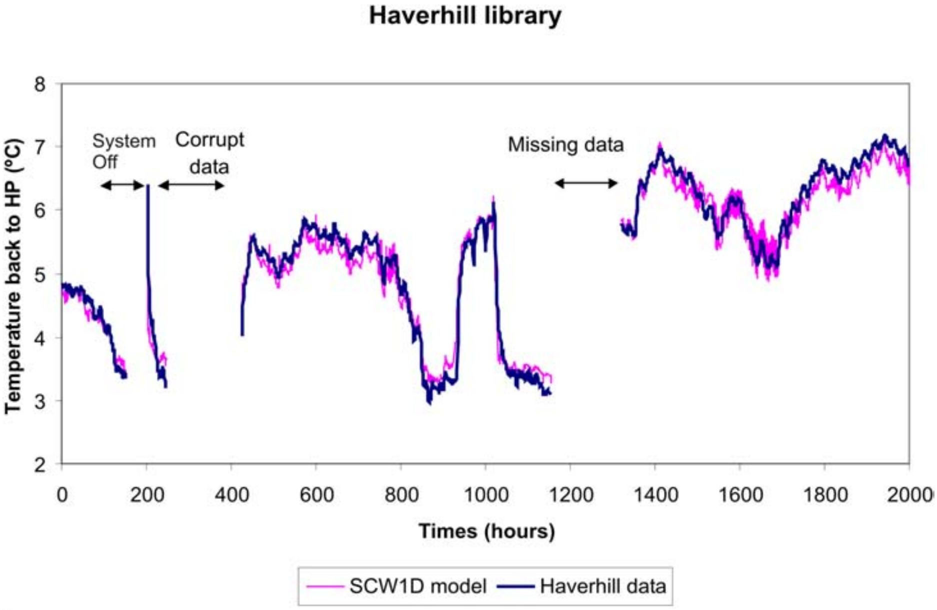

Figure 11. A comparison of calculated and measured temperatures at the outlet of the well using the Haverhill Public Library installation data.

At this site, although multiple SCWs are currently in use, the data used for this validation exercise were collected during the time period when only one standing column well was in operation (the first 2000 hours of the year 1996). The fluid temperatures exiting the SCW, returning to the heat pumps, are shown in Figure 11. For the first period marked "system off," the system is off, with no well pump power being consumed. During this time, the measured temperatures tend to drift toward the mechanical room temperature, and so are not shown. For the period marked "corrupt data," a failure in the instrumentation system (Orio 2005) caused the measured temperature difference across the SCW to go to zero, while the mean temperature remains approximately constant. Lacking any way to reconcile this inconsistency, the SCW was simulated for both time periods without flow or heat transfer between the system and well. For the period marked "missing data," the fluid temperature measurements were unavailable, but measurements of heat pump power were used to estimate the load imposed on the SCW.

This system has been designed so that whenever the well temperature drops below 4.4°C, a bleed cycle initiates. This automatic bleed diverts approximately 10% of the flow from returning to the wells. A bleed cycle typically lasts for 30 minutes. There is no bleed during summer operation.

Although well logs were available (Johnson 2003), results from the well drawdown tests were not. Consequently, thermal and hydraulic properties of the aquifer are estimated based on knowledge of the local geology (Domenico and Schwartz 1990). According to the general information provided by the US Geological Survey (USGS), the rock type for the Haverhill region is Ordovician and Cambrian sedimentary rock. The thermal conductivity of this type of rock is in the range of 2.50-6.60 W/(m·K) (USGS). The parameters used in the validation are given in Table 4. The undisturbed ground temperature is 10.0°C at the top of the well, and the natural

Table 4. Hydraulic and Thermal Properties of the Ordovician and Cambrian Sedimentary Rock

Hydraulic Properties

Hydraulic Conductivity (*K*) m/s	**Porosity (*n*)** (---)	**Specific Storage (S_s)** m^{-1}
1.00E-05	0.10	1.00E-05

Thermal Properties

Enhanced Thermal Conductivity (*k*) W/(m·K)	**Density (ρ)** kg/m^3	**Specific Heat (C_p)** J/(kg·K)
2.71	2200	1000

temperature gradient is 0.9°C/100 m. The parameter estimation method was used to find the actual value of the thermal conductivity. The estimated enhanced rock thermal conductivity used in this simplified model is 2.71 W/(m·K) (Deng 2004).

Figure 11 shows that, using the Haverhill Public Library data, there is good agreement between measured and calculated well outlet temperatures. The maximum difference is 0.9°C and the root mean square is 0.2°C. As noted earlier, these differences are thought to be due to the assumptions of there being a homogenous and isotropic aquifer, neglect of ground temperature gradient, vertical heat and fluid flow, and use of an estimated thermal conductivity. 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.

CONCLUSIONS AND RECOMMENDATIONS

This paper presents a one-dimensional numerical model for standing column well systems with the consideration of groundwater movement in the surrounding rock. This model has been validated against experimental data and a detailed two-dimensional numerical model (Spitler et al. 2002; Rees et al. 2004; Deng 2004). For the case study in this paper, the maximum difference in predicted heat pump entering fluid temperature between the simplified model and the detailed model was about 1.3ºC. Given that the simplified model is more than a hundred thousand times faster than the detailed model, allowing an annual simulation in two seconds instead of two weeks, this should be acceptable for either energy analysis programs or standing column well design programs.

The experimental validation of the model against two data sets shows good agreement between the simplified model and the experimental data. The root mean square errors of the simplified model are 0.8°C and 0.2°C, respectively, for the Mikler data set (1993) and the Haverhill data set (Henderson 2003). The maximum temperature differences between the simplified model and the experimental data are 1.5°C and 0.9°C. 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 were therefore estimated from the first portion of the experimental data sets.

Recommendations for future research include the following:

- Integrate the simplified model into building simulation software, such as HVACSIM+ and EnergyPlus. This will facilitate greater usage of the model by designers.
- 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.

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NOMENCLATURE

C_{pl} = specific heat of water, J/(kg·K)
C_{ps} = specific heat of solid, J/(kg·K)
K = hydraulic conductivity, m/s
k_{eff} = effective thermal conductivity, W/(kg·K)
k_l = thermal conductivity of water, W/(kg·K)
k_s = thermal conductivity of solid, W/(kg·K)
L = borehole depth, m
M = mass of water in the standing column well, kg
$\dot{m}$ = mass flow rate of water through the heat pump system, kg/s
n = porosity of rock
q = heat transfer flux applied to the ground per unit area of the borehole at the give time step, W/m^2 (a positive q value implies heat extraction in winter)
r_b = borehole radius, m
r_i = radius at location i, m
b = bleed rate, as a fraction of the total flow
R_b = borehole resistance, K m/W
S_s = specific storage, m^{-1}
T_b = borehole wall temperature, °C
T_f = average water temperature, °C
T_{fo} = water temperature leaving the well (returning to the heat pump), °C
T_{fi} = water temperature returning to the well, °C
T_{gw} = temperature of groundwater entering into the well, °C
V_{ri} = average linear groundwater velocity vector at radius r_i, m/s
ρ_l = density of water, kg/m^3
ρ_s = density of solid, kg/m^3

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APPENDIX A—CALCULATION OF SHORT-CIRCUITING HEAT TRANSFER RATE BY INTEGRAL METHOD

To consider the short-circuiting phenomenon in the standing column well, the model corrects the water temperature leaving the well (returning to the heat pump), T_{fo}, by the temperature difference caused by the short circuiting.

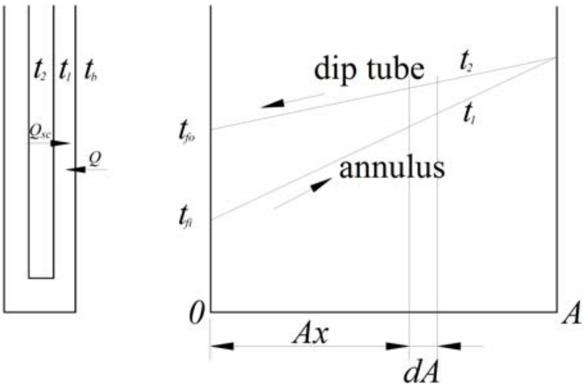

Figure A-1. Illustration of calculation of short-circuiting flux.

$$\Delta T_{sc} = \frac{q_{sc}L}{\dot{m}_w C_{p_w}} \tag{A-1}$$

where

ΔT_{sc} = temperature difference caused by the short circuiting, °C
q_{sc} = short-circuiting heat flux, W/m
L = borehole depth, m
$\dot{m}_w$ = mass flow rate of water exiting the well, kg/s
C_{pw} = specific heat of water, J/(kg·K)

For simplicity, in this study, the mass flow rates in the dip tube and the annulus are assumed to be equal. If the mass flow rates are assumed equal, the detailed analysis given by Deng (2004) may be simplified as follows:

$$q_{sc} = Q_{sc}/L \tag{A-2}$$

$$Q_{sc} = U\Delta T_m A = \left(\frac{UA\Delta T' + Q/2}{\varphi}\right)(1 - e^{-\varphi}) - \frac{Q}{2} \tag{A-3}$$

where

$$\Delta T' = T_{fo} - T_{fi} \qquad \Delta T_m = \frac{1}{A}\int_0^A \Delta T_x dA \qquad \varphi = \frac{2UA}{\dot{m}C_{pw}}$$

Q_{sc} = short circuiting heat transfer rate, W
Q = ground load, which is the heat transfer rate applied to the ground (W) (a positive Q value implies heating); this ground load is calculated with the borehole model and is used to set a boundary condition at the borehole wall in the finite difference model; the equations are solved iteratively until convergence is reached
T_{fi} = inlet water temperature, °C
T_{fo} = outlet water temperature without considering short-circuiting, °C
$\Delta T'$ = temperature difference between the inlet water and outlet water without considering short-circuiting, °C
ΔT_m = mean temperature difference
U = overall heat transfer coefficient between water in the dip tube and the annulus, based on the dip tube outer surface area, W/(m^2·K)
A = outer surface area of the dip tube, m^2
L = depth of the borehole, m
$\dot{m}$ = mass flow rate of water exiting the well, kg/s
C_{pw} = specific heat of water, J/(kg·K)

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