4666 (RP-1119)

A Study of Geothermal Heat Pump and Standing Column Well Performance

Simon J. Rees, Ph.D.
Member ASHRAE

Jeffrey D. Spitler, Ph.D., P.E.
Member ASHRAE

Zheng Deng
Student Member ASHRAE

Carl D. Orio
Member ASHRAE

Carl N. Johnson, Ph.D.
Member ASHRAE

ABSTRACT

Standing column wells can be used as highly efficient ground heat exchangers in geothermal heat pump systems, where hydrological and geological conditions are suitable. A numerical model of groundwater flow and heat transfer in and around standing column wells has been developed. This model has been used in a parametric study to identify the most significant design parameters and their effect on well performance. For each case in the study, performance has been evaluated in terms of minimum and maximum annual temperatures and design well depth. Energy consumption and annual costs have also been calculated. Groundwater "bled" from the system is one of the most significant parameters a system designer can use to improve well performance for a given load. The effects of bleed rate, well depth, and rock properties on heat transfer and energy consumption are discussed.

INTRODUCTION

Geothermal heat pump systems that use groundwater drawn 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 (i.e., similar construction to a domestic water well). Water is circulated from the well through the heat pump in an open loop pipe circuit. 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 the regions with suitable hydrological and geological conditions (Orio 1994, 1998, 1999).

The heat exchange rate in a standing column well is enhanced by the pumping action, which promotes movement of groundwater to and from the borehole and induces advective heat transfer. The fact that in such systems groundwater is circulated through the heat pump means that the fluid flowing through the heat pump system is closer to the mean ground temperature compared to systems with closed-loop U-tube heat exchangers. Accordingly, heat pump efficiency may be improved over that of other heat pump systems.

Most applications of SCWs in North America (for geological and hydrological reasons) have been in the Northeast and Pacific Northwest of the United States in addition to parts of Canada. These regions have lower mean ground temperatures and higher heating loads than other areas. Consequently, the SCW design has been focused on heat extraction capacity. Under normal operating conditions, all water extracted from the well is circulated through the heat pump system and returned to the well. The well temperature can be returned to one closer to the far-field temperature by "bleeding" off some of the system flow and discharging this proportion of the flow to some other well or watercourse. This induces further flow of groundwater into the well. This effect can be utilized to reduce the required well depth, protect the well against approaching freezing conditions, or to generally increase the heat exchange capacity for a given well depth.

A 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

Simon J. Rees is a senior research fellow at the Institute of Energy and Sustainable Development, De Montfort University, Leicester, United Kingdom. **Jeffrey D. Spitler** is a professor and **Zheng Deng** is a research assistant in the School of Mechanical and Aerospace Engineering, Oklahoma State University, Stillwater, Okla. **Carl D. Orio** is president and **Carl N. Johnson** is vice president at Water Energy Distributors, Inc., Atkinson, N.H.

assessed in terms of heat transfer rates, effective well depth, energy consumption, and costs (Spitler et al. 2002).

HEAT TRANSFER IN STANDING COLUMN WELLS

Conventional closed-loop heat exchangers in geothermal heat pump applications are often modeled assuming no groundwater flow and that the soil/rock can be considered as a solid. 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. The heat transfer processes in and around a standing column well are illustrated in Figure 1.

In addition to the conduction of heat through both the rock and the water, convective heat transfer occurs at the surfaces of the pipework and at the borehole wall and casing. 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.

The advective heat transfer due to the groundwater flow is always beneficial to the heat exchanger performance—whether the water is withdrawn from the top or the bottom of the well. In the cooling season, warm water is forced to flow *into* the rock and cooler groundwater flows back *out of* the rock near the point of suction. Conversely, during the heating season, cool water flows *into* the rock and warmer water flows *out of* the rock near the point of suction. The flow is therefore beneficial in either mode of operation.

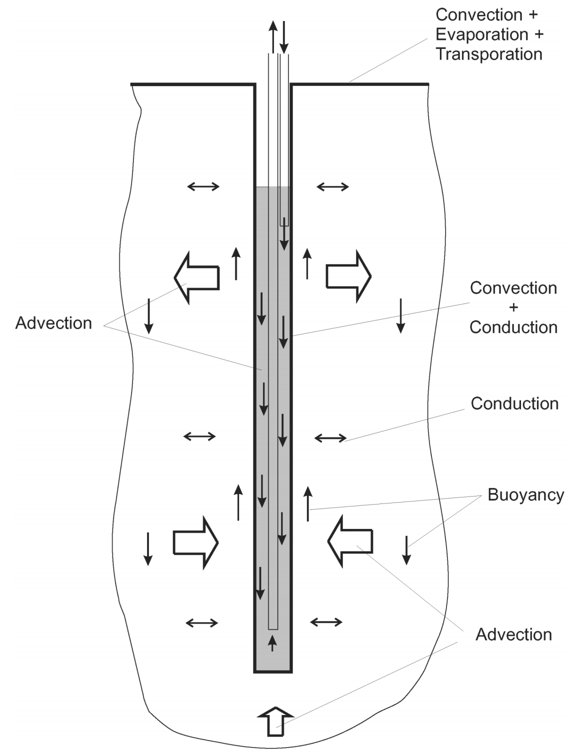

Figure 1 *A diagram showing the different modes of heat transfer in and around a standing column well.*

THE STANDING COLUMN WELL MODEL

Previous models of standing column wells (Mikler 1993; Oliver and Braud 1981; Braud et al. 1983; Yuill and Mikler 1995) have made a number of assumptions about the heat transfer between the different components of the well.

Groundwater flow in the lateral direction due to gross water movement arising from head gradients induced by adjacent rivers, local pumping, and changes in topology and geology on a larger scale have not been considered in this study. Consequently, it can be assumed that the groundwater flow and heat transfer are symmetrical about the centerline of the borehole. To model the groundwater flow and heat transfer surrounding the well, a finite volume model that uses a mesh in two dimensions (axial and radial) has been developed. The well borehole is modeled as a nodal network that is discretized over the length of the borehole. Fluid flow in the nodal model of the well borehole is modeled using control volumes that coincide with those of the adjacent finite volume mesh. Each model is described in further detail below.

THE GROUNDWATER FLOW MODEL

In order to model heat transfer and groundwater flow around the standing column well, it is necessary to solve two sets of partial differential equations. In this work, saturated flow has been assumed, so Darcy's equation is used to model saturated groundwater flow. The equation of flow is written in terms of head and is given by

$$\nabla \cdot (K \nabla h) = S_s \frac{\partial h}{\partial t}, \tag{1}$$

where

K = hydraulic conductivity, m/s (ft/h);
h = hydraulic head, m (ft);
S_s = specific storage; and
t = time, s (h).

In this type of problem with a radial-axial geometry, the static component of the head can be subtracted out—only differences in head induced by pumping cause groundwater flow.

Heat transfer in the ground is described by a form of the energy equation. We assume that the solid phase and fluid phase are in thermal equilibrium (at the same temperature at a given point) so that we consider the temperature as an average temperature of both phases. An effective thermal conductivity (k_{eff}) for the rock and fluid can be defined by

$$k_{eff} = nk_l + (1-n)k_s \,, \tag{2}$$

where

n = porosity;

k_l = thermal conductivity of fluid, W/m·K (Btu/h·ft·°F); and

k_s = thermal conductivity of solid, W/m·K (Btu/h·ft·°F).

The thermal mass of the rock is similarly given by $[n\rho_l C_{pl} + (1-n)\rho_s C_{ps}]$, where C_{pl} and C_{ps} are the specific heats of the liquid and solid, respectively. The energy equation is consequently defined (Bear 1972) for the porous medium as

$$[n\rho_l C_{pl} + (1-n)\rho_s C_{ps}]\frac{\partial T}{\partial t} + \rho_l C_{pl} V_i \nabla T - \nabla \cdot (k_{eff} \nabla T) = Q \,, \tag{3}$$

where

V_i = average linear groundwater velocity vector, m/s (ft/min);

n = porosity;

k_{eff} = effective thermal conductivity, W/m·K (Btu/h·ft·°F);

ρ = density, kg/m^3 (lbm/ft^3);

C_p = specific heat, J/kg·K (Btu/lbm·°F);

Q = source/sink, W/m^3 (Btu/h·ft^3);

l = water; and

s = solid (water saturated soil).

The second term only contains the thermal mass of the liquid, as heat is only advected by the liquid phase. The energy equation (Equation 3) and the equation for head (Equation 1) are coupled by the fluid velocity. The fluid velocity is obtained from the darcian groundwater flux as follows:

$$v = -\frac{K}{n}\nabla h \tag{4}$$

Hence, the solution to the energy equation depends on the velocity data calculated from Darcy's equation. Consequently, Darcy's equation and the energy equation are solved in sequence iteratively.

Heat transfer in the well bore is characterized in the radial (r) direction by convection from the pipe walls and borehole wall, plus advection at the borehole surface, and in the vertical (z) direction by advection only. The thermal model for the well bore can be described by a series of resistance networks, as shown in Figure 2. The thermal network at a particular vertical position varies depending on the presence of the suction and discharge pipes.

The Well Borehole Model

An energy balance can be formulated at each z plane in the well bore corresponding to the z plane in the finite volume model of the rock,

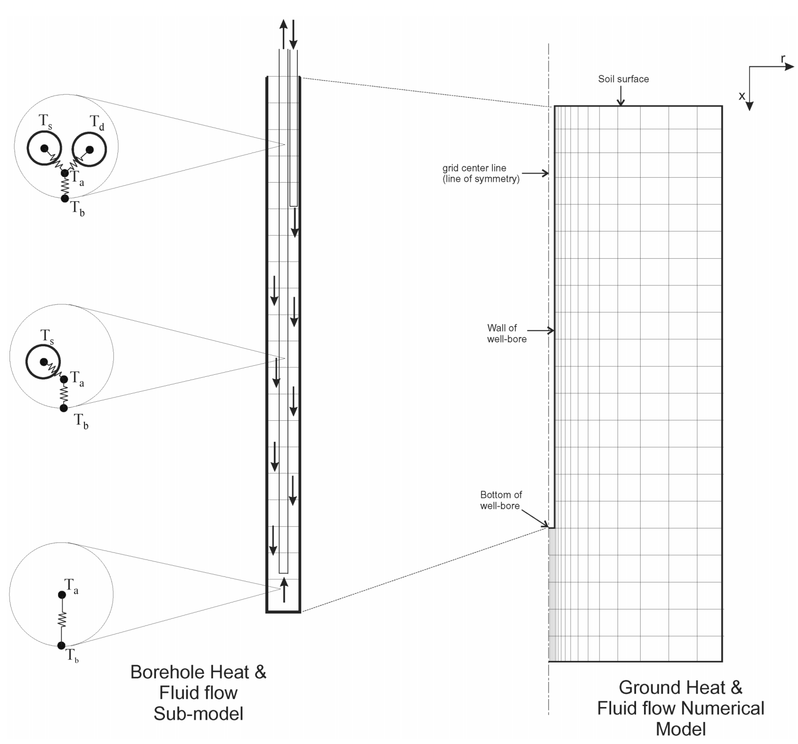

Figure 2 *A diagram showing the relationship between the well borehole and groundwater flow models.*

$$\frac{dT_{a,z}}{dt}V\rho c_p = q_{convection,suction\ tube} + q_{convection,discharge\ tube} + q_{convection,rock} + q_{advection,rock} + q_{advection,annulus}\ , \tag{5}$$

where

$T_{a,z}$ = fluid temperature in the annular region, °C (°F);
V = volume of water in the annular region, m^3 (ft^3);
ρ = density of water in the annular region, kg/m^3 (lbm/ft^3); and
c_p = specific heat of water, J/kg.K (Btu/lbm·°F).

Making use of the resistance network, the convective heat transfer rates are defined as

$$q_{convection,m} = \frac{1}{R_m}(T_m - T_{a,z})\ , \tag{6}$$

where

R = thermal resistance, °C/W (°F/ft), and
m = any of the surfaces: suction tube, discharge tube, and rock.

The thermal resistance based on the inside area is

$$R_m = \frac{1}{A_{i,m}}\left[\frac{1}{h_{i,m}} + \frac{r_i}{k_{pipe}}\ln\left(\frac{r_i}{r_o}\right) + \frac{r_i}{r_o}\left(\frac{1}{h_o}\right)\right]\ , \tag{7}$$

where

A = area, m^2 (ft^2);
r = radius, m (ft);
k = thermal conductivity, W/m·K (Btu/h·ft·°F);
i = inner surface;
o = outer surface;
h = convection coefficient, W/m·K (Btu/h·ft·°F);
= $\frac{Nu\ k_{fluid}}{D_h}$; and
D_h = hydraulic diameter, m (ft).

The second and third terms of Equation 7 do not apply to convective heat transfer at the borehole wall. The advective heat transfer rates in Equation 5 are defined as

$$q_{advection,n} = \dot{m}c_p(T_n - T_{a,z})\ , \tag{8}$$

where

$\dot{m}$ = mass flow rate of the water, kg/s (lbm/h), and
n = refers to each rock and the annular fluid at adjacent nodes.

For the fluid in each of the dip tubes, the energy balance is given by

$$\frac{dT_{tube,z}}{dt}V\rho c_p = q_{convection,annular\ region} + q_{advection,tube}\ , \tag{9}$$

where all terms are expressed as described above.

Now, Equation 5 can be expressed in discrete form to find $T_{a,z}$ and, likewise, Equation 9 can be expressed in discrete form for each tube, resulting in a system of simultaneous equations that can be solved using the Gauss-Seidel method. Upon convergence of the fluid temperatures, the heat flux to the borehole wall is calculated and passed to the finite volume model and used to set the flux boundary condition; the finite volume model, in turn, is used to calculate new temperatures at the borehole wall. This procedure is repeated at each time step until the borehole wall temperatures and fluxes at each z-level are consistent.

PARAMETRIC STUDY

This section describes the parametric study that has been used to determine the effect of key parameters on the performance of SCW systems. To examine the effects of particular parameters, one year of hourly building loads from a prototype building have been used to provide thermal boundary conditions for the SCW model. Simulations have been made using a whole year of load data. This allows the highly transient nature of the SCW system to be examined, especially during "bleed" periods.

The parametric study has been organized using a "base case" and calculating the system performance for this and other cases where a single parameter is varied in each case. (It was shown infeasible to consider all possible parameter combinations due to the intensive nature of each calculation). Variations in the following parameters have been studied:

- Rock thermal conductivity
- Rock specific heat capacity
- Ground thermal gradient
- Borehole surface roughness
- Borehole diameter
- Borehole casing depth
- Dip tube diameter and conductivity
- System bleed
- Bleed control strategy
- Borehole depth
- Borehole flow direction
- Rock hydraulic conductivity

All of the simulations have been made by using building loads calculated for a small office building in Boston, Mass. The building loads are determined by using building energy simulation software (BLAST 1986), and the construction is based on a real building in Stillwater, Okla. Further details of the building, systems and loads are given in Yavutzturk and Spitler (2000). The design data for the base case well design comes mostly from the well used by Mikler (1993). This well has a dip tube (suction tube) extending to very near the bottom of the well and discharge from the heat pump system is near the top. The ground conditions are assumed to be similar to those in the northeastern U.S. The base case thermal and hydraulic properties are taken from the mean values for karst limestone.

Power consumption and energy costs have been calculated for each case in the study and for water table depths of 5 m (16 ft) and 30 m (98 ft). Pumping costs were calculated by considering frictional pipe and fitting pressure losses for a typical piping arrangement. In addition to the frictional losses, the head required to achieve the various bleed rates was calculated. A schedule of monthly energy prices was used to find the final annual costs.

Parameter Values

In the parametric study, each case has one parameter value changed from those of the base case (except the cases that deal with different rock types). Calculations with differing well depths have been made to enable each parameter variation to be correlated with potential reduction/extension of borehole depth.

In addition to the calculations of well performance with constant rates of bleed, additional calculations were made using two strategies for controlling bleed operation. The modes of operation were:

1. *Deadband control:* In winter, a deadband of 5.83°C (42.5°F) to 8.6°C (47.5°F) is used. In summer, a deadband of 29.2°C (84.5°F) is used.
2. *Temperature-difference control:* A temperature difference between water back to and from the heat pump was used as the control parameter. Bleed was applied when the temperature difference was above 4.6°C (40.3°F).

In both cases the rate of bleed was 10%.

PARAMETRIC STUDY RESULTS

In the parametric study, only one parameter value was varied in each case, relative to the base case. The computationally intensive nature of the calculations has meant that it has not been feasible to make calculations with every combination of parametric values. Accordingly, in the presentation of the results, we show first how the maximum and minimum exiting fluid temperatures from the standing column well vary with a single parameter.

In an attempt to correlate changes in parametric values with effective changes in design borehole length, a number of simulations were made using the base case but with different

Table 1. Property Values Used in the Parametric Study

Parameter	Units	Key	Case				
			Base Case	1	2	3	4
Hydraulic Conductivity	m/s (gal/day/ft^2)	A	7.0E-5 (148.23)	1.0E-2 (21175.71)	1.0E-6 (2.118)	7.0E-10 (0.00148)	
Thermal Conductivity	W/m°C (Btu/h·ft·°F)	B	3.0 (1.73)	2.5 (1.44)	4.3 (2.48)	1.5 (0.865)	5.0 (2.88)
Specific Heat Capacity	kJ/m^3·°C (Btu/ft^3·°F)	C	2700 (40.27)	21300 (317.69)	5500 (82.03)		
Geothermal Gradient	°C/m (°F/100ft)	D	0.006 (0.329)	0.003 (0.165)	0.018 (0.987)		
Surface Roughness	m (ft)	E	1.5E-3 (4.92E-3)	3.0E-4 (9.84E-4)	9.0E-3 (2.95E-2)		
Borehole Diameter	m (in.)	F	0.1524 (6.0)	0.1398 (5.5)	0.1778 (7.0)		
Casing Depth	% Well Depth	G	0	50	33	25	
Dip Tube Diameter	m (in.)	H	0.1016 (4.0)	0.0762 (3.0)	0.1143 (4.5)	With insulation	
Dip Tube Configuration	-	J	Suction at bottom	Discharge at bottom			
Constant Bleed Rate	%	K	0	2.5	5	15	20
Controlled Bleed Rate	%	L	-	5 Dead-band	10 Dead-band	10 Temp. Diff.	
Rock type	-	M	Karst Limestone	Dolomite	Fractured Igneous	Sandstone	
Well Depth	m (ft)	N	320 (1050)	240 (787)	280 (919)	360 (1181)	400 (1312)

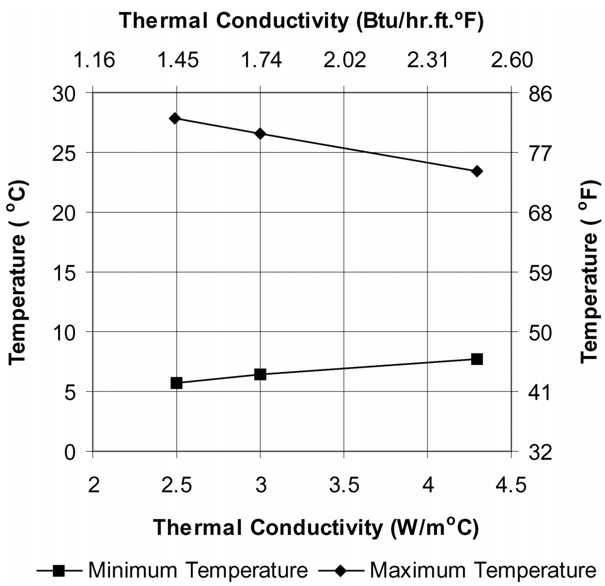

Figure 3 *The effect of rock thermal conductivity on peak well exit temperatures.*

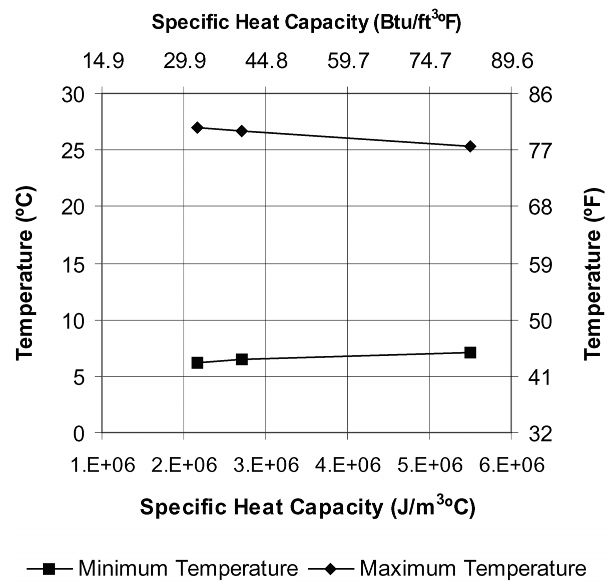

Figure 4 *The effect of rock specific heat capacity on peak well exit temperatures.*

borehole lengths. These data have been used to find linear relationships between minimum and maximum temperatures and borehole length. We can then estimate (assuming this relationship to be linear in all cases) the effect that each parametric variation has in terms of the design well depth.

Rock Thermal and Hydraulic Properties

The rock (geological formation) thermal and hydraulic properties that are significant to heat transfer around the borehole are thermal conductivity, specific heat, and hydraulic conductivity. Conduction of heat around the borehole is dependent on the rock thermal conductivity and specific heat in much the same way as in a closed-loop vertical ground heat exchanger. The resulting minimum and maximum temperatures from the annual calculations with different thermal conductivities and specific heats are shown in Figures 3 and 4, respectively. Both of these parameters have a significant effect on borehole performance. Increased thermal conductivities result in higher fluxes at the borehole wall for given temperature differences. Higher specific heats result in greater damping of the fluctuations in load.

Flow of groundwater is proportional to hydraulic conductivity and head gradient (Darcy's law) in the same way that heat flux is proportional to thermal conductivity and temperature gradient (Fourier's law). Hence, increased thermal conductivity could be expected to increase the advective heat transfer around the borehole in a beneficial way. The resulting minimum and maximum annual temperatures from the calculations with different hydraulic conductivities are shown in Figure 5. This shows that the performance is actually reduced at some intermediate value of hydraulic conductivity. Detailed examination of the convective and advective heat fluxes along

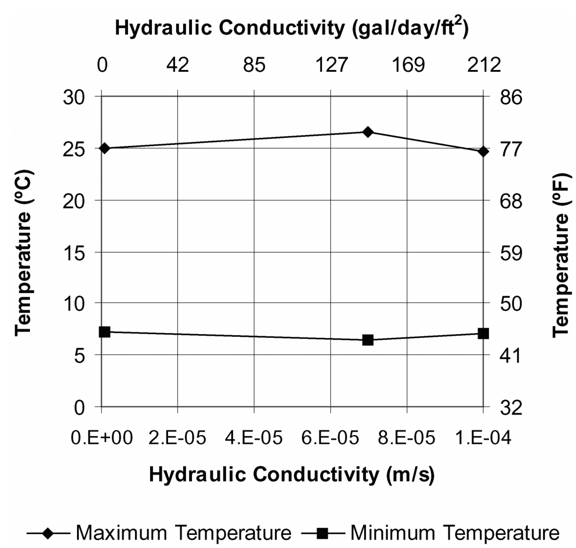

Figure 5 *The effect of rock hydraulic conductivity on well exit temperatures.*

the length of the borehole have shown that there is some trade-off between higher advective fluxes with increased hydraulic conductivity and lower convective heat transfer. Although higher hydraulic conductivities increase the flow of water to and from the borehole into and out of the surrounding rock, the flow along (up and down) the borehole is correspondingly reduced. This, in turn, reduces the convective heat transfer at the borehole wall. Hence, there is some trade-off between increased advective heat transfer and reduced convective heat transfer.

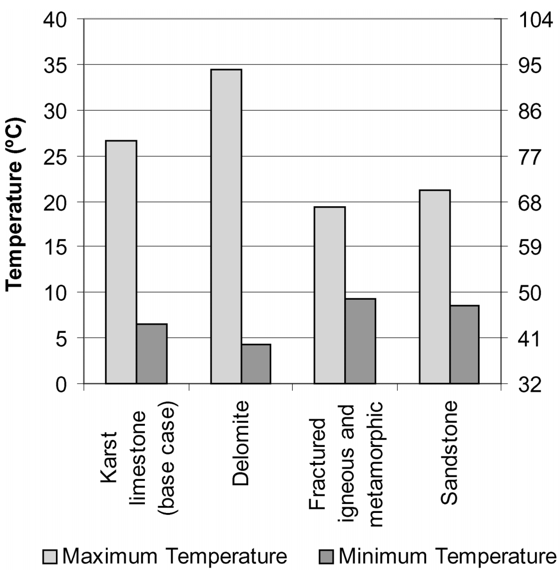

Figure 6 *The effect of rock type on the well exit temperatures.*

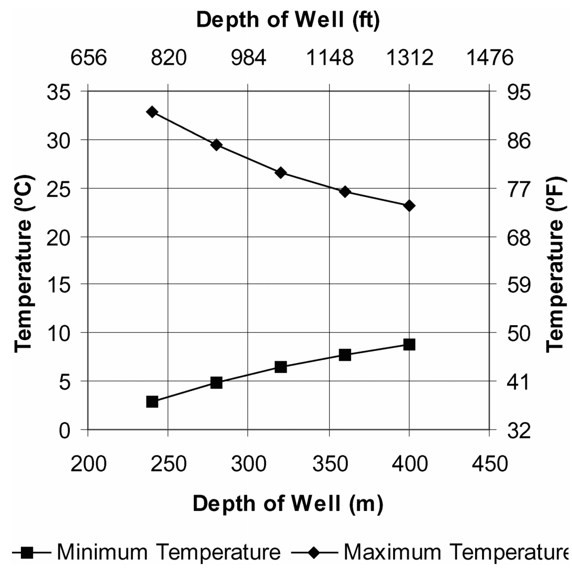

Figure 7 *The effect of well depth on the water temperature back to the heat pump.*

The sensitivity to rock thermal and hydraulic properties was examined by making calculations with combinations of property values that are representative of certain rock types. In these cases the values of thermal conductivity, hydraulic conductivity, and porosity were chosen to be representative of karst limestone (the base case), dolomite, fractured igneous rock, and sandstone. The resulting minimum and maximum temperatures are compared in Figure 6. Even though the fractured igneous rock and sandstone cases have the lowest hydraulic conductivity, they both perform better than the base case. This is presumed due to the fact that they have the highest thermal conductivity. Similarly, the dolomite case performs poorly and has the lowest thermal conductivity. The effect of thermal conductivity is more dominant than that of hydraulic conductivity.

Well Design Parameters

The system designer, for a given location, has control over only a few design parameters, the main ones being well depth, diameter, and the rate of bleed. In this study, calculations were made with borehole depths in the range 240-400 m (787-1312 ft) and with loads and other parameters the same as the base case. As borehole depth is reduced, the amount of load applied per unit length of borehole increases accordingly. Changing the borehole length in this range can be seen to have a significant effect on exiting fluid temperatures. The trend is also slightly nonlinear. This might be expected as, in addition to the load per unit depth changing, end effects become more significant at reduced depths. Also, due to the geothermal temperature gradient applied, the mean ground temperature becomes lower with shorter depths.

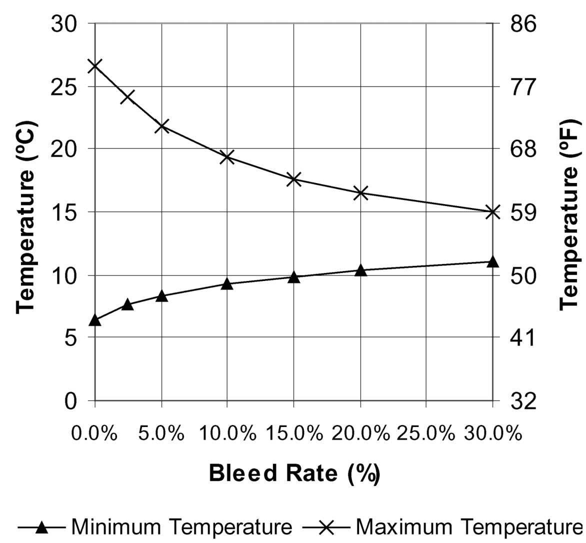

Figure 8 *The effect of bleed rate on the water temperature back to the heat pump.*

The bleed parameter calculations were made by making a one-year simulation. The results (Figure 8) show how significantly the minimum and maximum temperatures can be moderated by introduction of bleed. The effect of increased bleed can be seen to be nonlinear. This, in itself, might be expected from the nature of the governing heat transfer equations (Equation 3). The most significant changes compared with the base case (zero bleed) occur in the range 0% to 15%. However, energy savings and reduction in well depth may justify higher rates of bleed.

The combined effects of different rates of bleed and different well depths are summarized in Figure 9. In these cases, borehole depth varied from 240 to 360 m (787-1181 ft) and bleed rates were 0%, 5%, and 10% with the loads kept the same. The variation of borehole depth in this range can be seen to have a significant effect on the exiting water temperature if bleed rate is zero. But if bleed rate is set as 5% or higher, the borehole depth can be seen to have a little effect on the SCW performance: different borehole depths show almost the same exiting water temperatures. As bleed rate is increased, the flow to the heat pump approaches the temperature of the far-field groundwater (13.1°C [55.6°F] in this case). Correspondingly, the borehole depth becomes less significant in itself. This trend is seen in the results.

These results show clearly how bleed can be used to moderate the temperature of the water drawn from the well. This can be very important in protecting the system against freezing in heating mode. It also shows how well depth might be reduced—and, consequently, initial costs—by reliance on bleed. However, there are practical considerations that also determine the minimum depth of borehole and maximum bleed. First, the pumping capacity of a well is limited and also dependent on depth. Consequently, it may not be possible to have a shorter well with a high rate of bleed. Second, high rates of bleed require that significant amounts of water be discharged appropriately. Again, this may not be practical.

Bleed Control Strategy

In most cases, it is not necessary to continuously apply bleed and some form of bleed control is used. Control according to deadband temperatures and according to system temperature difference were simulated. Figure 10 compares the exiting water temperature in non-bleed operation with deadband bleed control operation over the first 800 hours. The times at which bleed begins or stops are also indicated.

In the base case, the well temperature is close to freezing. Continuous bleed at 10% increases the minimum temperature significantly to 7.7°C (45.8°F). For the calculations where deadband and temperature-difference bleed control was modeled, the minimum water temperature back to the heat pump was increased to 5.3°C (41.6°F), and 6.0°C (42.8°F), respectively. Consequently, if the primary concern is to avoid freezing of the borehole, intermittent bleed may suffice. There was little difference found between the two methods of control.

System Energy Consumption and Costs

System energy consumption (heat pump + circulating pump) and associated costs have been calculated for each case. The average annual power consumption has been expressed in terms of power consumption per unit of heating/cooling (kW/ton). The calculations have been made for water table depths of 5 m (16 ft) and 30 m (98 ft) so that the change in pumping costs with water table depth can be considered. With a water table depth of 5 m (16 ft), the base case operating cost is $1482 per annum with a peak power consumption ratio of 1.13 kW/ton. With a water table depth of 30 m (98 ft), the base case operating cost is $1504 per annum with a peak power consumption ratio of 1.13 kW/ton.

The parameters that had little effect on the minimum and maximum well temperatures correspondingly change the annual costs insignificantly. The most significant factors influ-

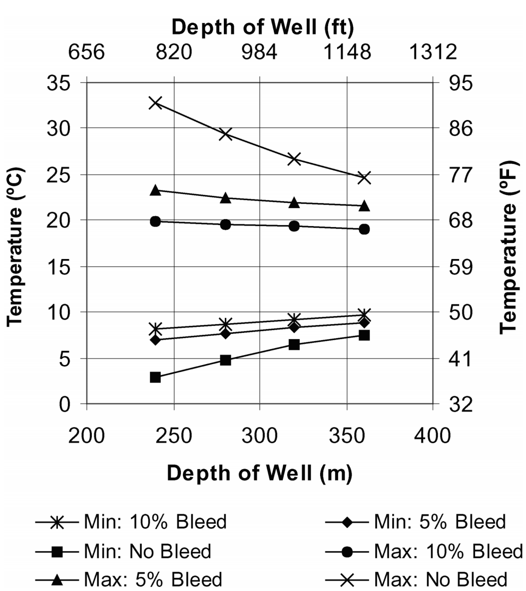

Figure 9 The combined effect of depth of borehole and bleed rate on the minimum and maximum water temperature back to HP.

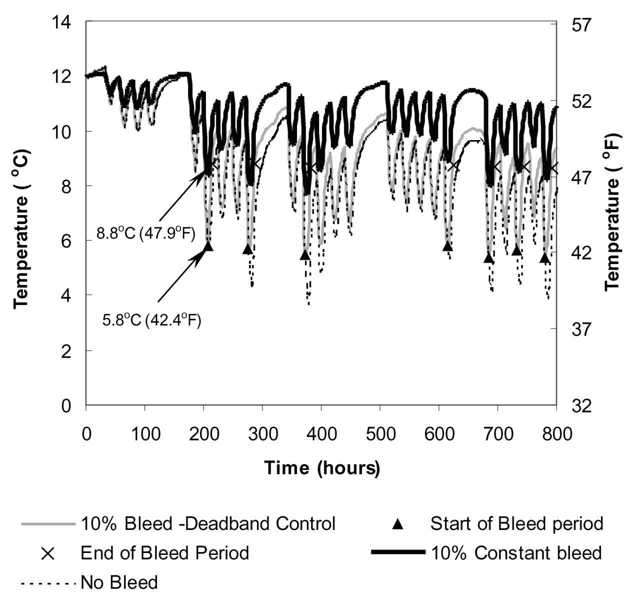

Figure 10 Comparison water temperature back to the heat pump between non-bleed case, constant bleed, and deadband bleed control case.

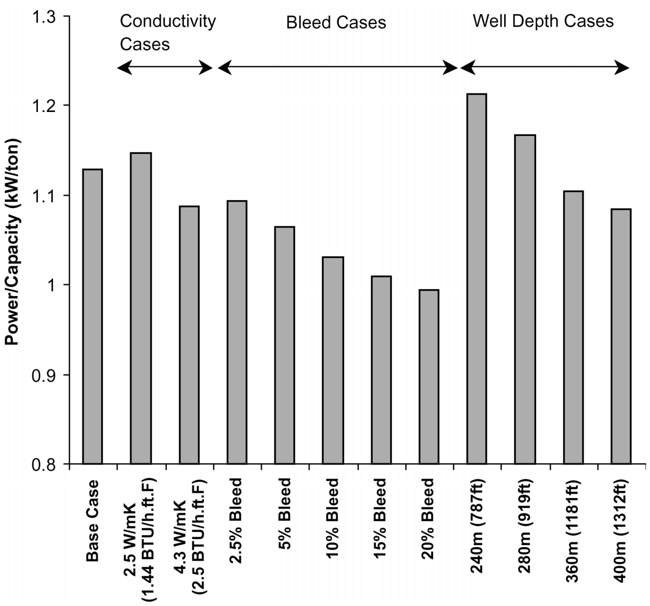

Figure 11 *The ratio of peak power consumption to heat transfer rate (water table = 5 m).*

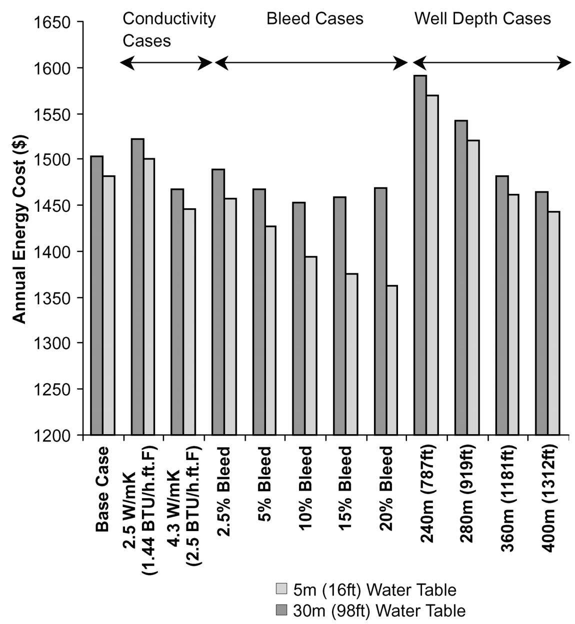

Figure 12 *Comparison of annual energy costs for water table depths of 5 m and 30 m.*

encing the cost are length, thermal conductivity, and bleed rate. In the cases with different well depth and thermal conductivity, the energy consumption is improved by increasing the heat pump efficiency when the well temperatures are improved (i.e., longer length and higher conductivity).

The energy costs and efficiency can be most significantly improved by introducing higher rates of bleed. In these cases, the water table depth has a significant effect on costs. The costs for the cases with different bleed rates and water table depths are compared in Figure 11. When the water table is at a depth of 5 m, the higher cost of pump energy consumption at higher rates of bleed is outweighed by reduced heat pump energy costs. Similarly, there appears to be little benefit in controlling the system to reduce the number of hours operating with bleed (i.e., just to guard against freezing of the borehole). When the water table is at a depth of 30 m, and higher rates of bleed (>10%), the higher cost of pump energy consumption starts to outweigh the benefit of improved heat pump efficiency.

CONCLUSIONS

A numerical model of a standing column well has been developed using a finite volume method to calculate groundwater flow and heat transfer and a coupled nodal model of the well bore. This model has been employed in a parametric study of standing column well performance. A base case design was developed with parametric values representative of common standing column well installation conditions. Several calculations were made, over a one-year operating period, where a single design parameter value is varied relative to the base case. This has enabled the effect of and significance of each design parameter to be studied.

The study has confirmed many of the standing column well performance characteristics found in practice. Better performance is possible where thermal and hydraulic conductivities are higher and the water table is higher. Indeed these are the characteristics of the regions in which current installations are found. In practice, the designer, for a given location, has no control over the thermal and hydraulic properties of the geological formation. The designer does have control however, over the main borehole parameters, such as length, diameter, dip tube size, and material, in addition to the system bleed rate and controls. Of these parameters, the length and bleed have been shown to affect performance most significantly—other parameters relate to only secondary effects. The results of the study show that introduction of bleed flow can dramatically improve the performance of the well. Significant improvements in performance were found with only moderate rates of bleed (5% to 15% of system flow).

Bleed may be employed for the following purposes:

- To reduce the required well depth for a given heat transfer rate, and consequently reduce initial costs.
- To improve energy efficiency by moderating fluid temperatures and increasing the efficiency of the heat pump.
- To guard against freezing in the well during system heating operation.

In practice, however, there may be a number of limitations on the amount of bleed that can be achieved. The maximum bleed achievable may be limited by well pumping capacity and practical difficulties in disposing of the bleed water.

Annual energy consumption has been estimated for each case in the parametric study. Results show that poorest energy performance occurs in cases with the least favorable thermal and hydraulic conductivities. The lowest energy costs are found in cases where bleed is introduced and heat pump efficiency is improved. Where the water table is high, the increased pump power when bleeding is not significant and the greatest efficiencies are when bleed rate is maximized. However, when the water table is lower, pump power requirements increase more significantly when bleed is introduced. The benefits of higher rates of bleed (> 10% in this study) are then outweighed by the increased pumping costs. This situation is probably different at higher rates of bleed where variable frequency drives are used (a case was not studied in this work).

Due to the computationally intensive nature of the calculations required for a detailed study of standing column well performance such as this, it is unlikely that the models developed in this work would be directly suitable for use in design tools. The nonlinear characteristics of the heat transfer performance of standing column wells also means that simplified analytical methods are difficult to apply. However, in the future it may prove possible to develop simpler design methods by reference to the detailed results of this work.

ACKNOWLEDGMENTS

This work has been completed under ASHRAE research contract "Studies Applied to Standing Column Well Design, ASHRAE 1119-RP." We wish to thank the TC 6.8 project monitoring subcommittee for their help and guidance during the project. We would also like to thank Mrs. W. Lewis for her assistance in preparing this paper.

REFERENCES

Bear, J. 1972. *Dynamic of fluids in porous media*. New York: Dover Publishing, Inc.

BLAST. 1986. BLAST (Building Loads and System Thermodynamics). Urbana-Champaign: University of Illinois, BLAST Support Office.

Braud, H., H. Klimkowki, and J. Oliver. 1983. Earth source heat exchanger for heat pumps. *Transactions of ASAE*. 26:1818-1822.

Mikler, V. 1993. A theoretical and experimental study of the "energy well" performance. Masters thesis, The Pennsylvania State University.

Oliver, J., and H. Braud. 1981. Thermal exchange to earth with concentric well pipes. *Transactions of ASAE*. 24(4): 906-910.

Orio, C.D. 1994. Geothermal heat pumps and standing column wells. *Geothermal Resources Council Transactions*. 18: 375-379.

Orio, C.D. 1998. Vertical earth coupling kelvin line theory. Technical bulletin #43. Water and Energy Systems Corporation, Atkinson, N.H., pp. 10.

Orio, C.D. 1999. Geothermal heat pump applications industrial /commercial. *Energy Engineering* 96(3): 58-66.

Spitler, J.D., S.J. Rees, Z. Deng, A. Chaisson, C.D. Orio, and C. Johnson. 2002. R&D Studies Applied to Standing Column Well Design, ASHRAE 1119-RP Final Report Atlanta: American Society of Heating, Refrigerating and Air- Conditioning Engineers, Inc.

Yavuzturk, C., J.D. Spitler. 2000. Comparative study to investigate operating and control strategies for hybrid ground source heat pump systems using a short time-step simulation model. *ASHRAE Transactions* 106(2):192-209.

Yuill, G.K., and V. Mikler. 1995. Analysis of the effect of induced groundwater flow on heat transfer from a vertical open-hole concentric-tube thermal well. *ASHRAE Transactions* 101(1): 173-185.

DISCUSSION

H. Ezzat Khalifa, Professor, Director EQS Center, Syracuse University, Syracuse, N.Y.: (1) Were the depth/ton values shown for bled or unbled systems? (2) What would it be for unbled?

Simon Rees et al.: The authors presented a numerical model of the standing column well and included results of a number of parametric studies comparing with a "no bleed" base case. These studies included, among others, well depth, thermal conductivity, and bleed rate. In all studies, no bleed was included except, of course, in the study of various levels of bleed rate.

Experience shows that greater capacity rates (tons/100 ft) are achieved with deeper wells. For example, a 1500 foot well with 10% bleed (~10 GPM) has a capacity of 30 tons (2 tons/100 ft). A 500 ft well with 10% bleed will have a capacity of 6 tons (1.2 tons/100 ft). The difference is due in part to the higher flow rate in the deeper well.

C. Bloodford, Stanford, Conn.: Geographic area for standing column well: soil/rock type critical; drilling costs important.

Rees et al.: Soil type is not critical, as the wells are always steel cased through the soil overburden into the solid bedrock.

Most rock types are acceptable. Connecticut has many standing column well systems in operation, and experience has shown that near surface bedrock, reasonable static water levels and clean water are present in all parts of the state. SCW costs, complete, including drilling, are in the range of $1,200 to $1,500 per ton in the northeast for deeper wells.

Gregor P. Henze, Assistant Professor, University of Nebraska, Omaha, Neb.: Why are the SCW heat pump applications found only in the small area of the NE shaded blue on your slide? Heat limits the geographical applicability of these systems?

Rees et al.: The SCW has been applied most successfully in the northeast because of near surface bedrock and the presence of clean water at reasonable static levels. Any area of the world sharing these characteristics could make equally successful applications.

Groundwater temperatures below 45°F may have limited applicability in heating, but only in the necessity of making the ground coupling larger.

Rees et al.: The standing column well (SCW) was first developed in the mid 1970s to respond to the need of geothermal systems in northern Maine. Maine wells have very poor water yields, as the dense rock is poorly fractured (the method was used in that area until the early 1980s, when the commercial use of geothermal became of general interest). The method was employed by geothermal designers (Orio et al.) at that time to solve the dilemma of "where do you put all that water?" It became quickly noted that the SCW also provided a source of high water flow for large geothermal applications. The SCW had, until the late/mid-1990s, been submerged beneath the "closed-loop" methods that had been generously promoted by plastic pipe and trenching manufacturers. During the 1990s, the SCW was promoted by the Association of Energy Energizers (AEE) and ASHRAE, and the commercial market came into its own. The SCW is now recognized by ASHRAE; ISPHA taught the SCW for the first time this last fall in the certified design course. The SCW, with a lower first cost, essentially unlimited in system sizing and higher efficiency, has finally come into its own, particularly as an answer to very large commercial systems.