

R&D STUDIES APPLIED TO STANDING COLUMN WELL DESIGN

ASHRAE 1119-RP

FINAL REPORT

July 2002

Jeffrey D. Spitler
Simon J. Rees
Zheng Deng
Andrew Chiasson

Oklahoma State University
School of Mechanical and Aerospace Engineering

Carl D. Orio
Carl Johnson

Water and Energy Systems Corporation

R&D STUDIES APPLIED TO STANDING COLUMN WELL DESIGN

ASHRAE 1119-RP

FINAL REPORT

July 2002

Jeffrey D. Spitler
Simon J. Rees
Zheng Deng
Andrew Chiasson

Oklahoma State University
School of Mechanical and Aerospace Engineering

Carl D. Orio
Carl Johnson

Water and Energy Systems Corporation

Contents

Contents	iii
Executive Summary	5
1.0 Introduction.....	9
1.1 Previous Work.....	11
1.2 Objectives and Approach.....	19
1.2.1 Task 1: Compilation and Analysis of Field Data	20
1.2.2 Task 2: Mathematical and Computer Modeling	20
1.2.3 Task 3: Parametric Study	21
2.0 Survey of Standing Column Well Installations	22
2.1 SCW Installation Survey Findings.....	22
2.1.2 Well Data	22
2.1.3 SCW Construction	27
2.1.4 Operating Strategies and Characteristics	28
2.1.5 Bleed Flow	28
2.1.6 Multiple Standing Column Well Systems.....	28
2.2 Installations with detailed operating data	29
2.2.1 Maine Audubon Visitor's Center	29
2.2.2 Residence Raymond, ME.....	29
2.2.3 Hotel, Scarborough, ME	30
2.3 Future Installation Monitoring and Characterization.....	32
3.0 Geological and Hydrogeological Characteristics of Standing Column Well Installations	33
3.1 Hydraulic And Thermal Properties Of Soils And Rocks	33
3.2 Ground-Water Regions Of North America	36
3.3 Regions With Standing Column Well Installations	41
3.3.1 Northeastern Appalachians Region.....	41
3.3.2 Appalachian Plateaus and Valley and Ridge Region.....	41
3.3.3 Piedmont and Blue Ridge Region.....	43
4.0 The Standing Column Well Numerical Model	45
4.1 Heat Transfer in Standing Column Wells	46
4.2 The Numerical Method	48
4.2.1 The calculation procedure	48
4.2.2 The Finite Volume Model.....	49
4.2.3 Application to Ground-water flow and Heat Transfer	55
4.3 The Borehole Model	58
4.3.1 The Borehole Numerical Model	60
4.3.2 Convective Heat Transfer In the Borehole	61
5.0 Parametric Study.....	65
5.1 The Base Case	65
5.1.1 Building Loads	65
5.1.2 Base Case SCW Design	67
5.2 Parameter Values	68
5.3 System Energy Calculations	72

5.3.1 System pressure drop without bleed	72
5.3.2 System pressure drop with bleed	73
5.3.3 Heat pump model.....	74
5.3.4 Circulating pump model	75
5.3.5 Frictional Pressure Losses.....	75
5.3.6 Electricity costs.....	77
6.0 Parametric Study Results	78
6.1 Calculated Ground-Water Flows and Head Distribution.....	78
6.2 Parametric Study Results	83
6.2.1 Thermal conductivity.....	88
6.2.2 Specific heat capacity.....	88
6.2.3 Geothermal gradients	88
6.2.4 Rock hydraulic properties	90
6.2.5 Borehole surface roughness	91
6.2.6 Borehole diameter.....	92
6.2.7 Casing depth.....	93
6.2.8 Dip tube insulation and diameter	93
6.2.9 Bleed rate	95
6.2.10 Borehole depth.....	95
6.2.11 Rock type	96
6.2.12 Bleed control strategy	97
6.2.13 Reversed flow configuration.....	99
6.2.14 Impact of well bore diameter on storage capacity	100
6.2.15 Varied depth with different bleed rates.....	102
6.2.16 System Energy Consumption and Costs	102
7.0 Conclusions	113
References	117
Appendix A: Questionnaire Sent to SCW Installers	120

Executive Summary

This report discusses the work of the ASHRAE research project 'R&D studies applied to standing column well design (1119-RP)'. The work has consisted of three major elements:

1. Survey and characterization of standing column well technology. This has included,
 - Survey and characterization of existing standing column well technology and installation practice
 - Collection and data from existing well installations
 - Characterization of geological and hydrological conditions in regions where standing column wells have been applied.
2. Development of a detailed model of a standing column well and surrounding geological formation.
3. A Study of the effects of and significance of standing column well design parameters. This has entailed using the model to calculate annual fluid temperatures driven by characteristic building loads.

Geothermal heat pump systems that use ground-water drawn from wells in an 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 ground-water up to the level of the water table. 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 geological conditions.

Standing column well systems share the same advantages, in terms of energy efficiency, environmental benefits, low maintenance etc. as other forms of geothermal heat pump system. The heat exchange rate in a standing column well is enhanced by the pumping action, which promotes movement of ground-water to and from the borehole. The higher heat exchange rate and the fact that such systems are open loop 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.

Most standing column well geothermal heat pump systems to date have been residential applications. A number of small commercial applications with multiple wells are known to exist. In order for a standing column well to be feasible the geological and hydrological conditions have to be such that a significant flow of water can be continually pumped from the well. This restricts the geographical locations where standing column wells are feasible (this is discussed in detail in Section 2 and 3 of this report). Historically 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 is focused on heat extraction capacity.

Data from 34 wells at 21 locations have been collected and are believed to be representative of current installation practice and geographical distribution. These installations all have heating dominated loads. Heat extraction has accordingly been the main focus of these well and system designs. Bleeding of the well to induce flow of ground-water at more moderate temperatures into the well is a key feature of the well and system designs.

Construction differences existing in the reported standing column wells relate in part to the depth of the well rather than any other influencing parameter. The location and hydraulic properties of the different 'ground-water regions' of North America have been presented. The regions where standing column well installations have been identified are all in the Northeast of North America. These regions are the (i) Northeastern Appalachians, (ii) Appalachian Plateaus and Valley and Ridge and, (iii) Piedmont and Blue Ridge regions. Each of these regions has igneous or metamorphic rock where relatively high well capacities and good water quality is available.

Previous models of standing column wells (Mikler 1993, Oliver and Braud 1981) have made a number of assumptions about the heat transfer between the different components of the well. The numerical model developed in this work is composed of two parts: a nodal model of the borehole components and a finite volume model of the ground-water flow and heat transfer in the surrounding rock. The model allows the explicit treatment of the advective heat transfer induced by the ground-water flow. This is of particular importance for the realistic treatment of bleed operation

The numerical model has been employed in a parametric study of standing column well performance. A base case design was developed with parameter 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. Because of the highly intensive computational nature of the calculations (six computers were employed continuously over a 24 week period) only a limited number of cases could be considered.

The well performance has been characterized by minimum and maximum exiting fluid temperature and equivalent design borehole length. The performance was found to be most sensitive to the following parameters:

- Bleed rate
- Borehole length
- Rock thermal conductivity
- Hydraulic conductivity

A number of other parameters affect the convective heat transfer in the borehole but were found in themselves to have only a secondary effect on well performance.

Performance was found to vary with bleed rate in a highly nonlinear manner and a number of interesting characteristics have been identified.

- Performance can be improved dramatically by introducing bleed. However, at higher bleed rates (greater than 10% in this study) there is little further gain in performance. (In certain installations, low borehole temperatures in peak heating conditions may still require bleed rates higher than 10%).
- With increasing bleed rate sensitivity to borehole length decreases. This is thought to be because with shorter borehole lengths ground-water flow velocity would theoretically increase – increasing the significance of the advective heat transfer – for the same bleed flow rate. In practice it may not be possible to maintain higher bleed flows at shorter borehole depths as the flow is limited by the hydrological conditions i.e. well flow capacity.
- As hydraulic conductivity increases there is a trade-off between convective and advective heat transfer at the borehole wall – increasing advection through the wall reduces convection along the wall. This means that very high hydraulic conductivities do not necessarily result in better performance than moderate values.

Annual energy consumption has been estimated for each case. Results show that poorest energy performance occurs in cases with the least favorable thermal and hydraulic conductivities. As may be expected, energy performance is not sensitive to the parameters that have already been noted to have little effect on standing column well thermal performance. 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).

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 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 higher bleed rates (calculations were made with bleed rates up to 20%) can significantly improve overall energy performance and can enable the borehole length to be reduced significantly. In practice however, there maybe a number of limitations on the amount of bleed that can be achieved, such as, limited well pumping capacity and practical difficulties in disposing of the bleed water.

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 non-linear 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.

Following this project, what remains to be done? There are two fundamental areas of investigation necessary to provide design methodologies and tools for designers. First, some experimental validation of the detailed simulation tool developed for this project needs to be done. Second, once the detailed simulation tool has been validated, it may be used to investigate various procedures for simplified simulations.

Such simulations might be as simple as using the line source analysis with an “enhanced” thermal conductivity. If so, the detailed simulation procedure could be used to determine an appropriate method for modifying the thermal conductivity. More sophisticated, but still much faster, simulations which combine a line source with water storage in the borehole and where bleed is treated as some combination of groundwater flowing directly to the borehole and an enhanced thermal conductivity may also be imagined. Finally, a numerical model might be used if some pre-computed groundwater flows were used whenever bleed occurred. A variety of simple simulation models could be compared to detailed simulation results to identify the best procedure.

Once a simplified simulation tool has been developed, it will also be desirable to develop more thorough design guidelines. These may include recommended in-situ tests, e.g. thermal conductivity and well draw-down tests; recommended design details, e.g. system configuration and material specifications; acceptable water quality, etc.

1.0 Introduction

This report discusses the work of the ASHRAE research project 'R&D studies applied to standing column well design (1119-RP)'.

Geothermal heat pump systems that use ground-water drawn from wells in an open loop arrangement are commonly known as Standing Column Well (SCW) systems. The ground heat exchanger in such systems consists of a vertical borehole (typically 150-200mm diameter [6-8 ins.]) which is filled with ground-water up to the level of the water table. Water is circulated from the well through the heat pump in an open loop pipe circuit (Figure 1.1). SCW systems are also referred to in the literature as “turbulent wells”, “Energy Wells”, “Concentric wells”, “Recirculating wells”, “Geo-wells”, “Thermal wells”, and “Closed-loop, open-pipe systems”. 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 geological conditions.

Standing column well systems share the same advantages, in terms of energy efficiency, environmental benefits, low maintenance etc. as other forms of geothermal heat pump system. The heat exchange rate in a standing column well is enhanced by the pumping action, which promotes movement of ground-water to and from the borehole. Consequently heat transfer with the surrounding rock takes place by advection in addition to conduction. The higher heat exchange rate and the fact that such systems are open loop 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.

Most standing column well geothermal heat pump systems to date have been residential applications. In residential systems usually only one well is required and also can be used for domestic water purposes. A number of small commercial applications with multiple wells are known to exist. In order for a standing column well to be feasible the geological and hydrological conditions have to be such that a significant flow of water can be continually pumped from the well (typically several kg/s [gpm] from a single well). This restricts the geographical locations where standing column wells are feasible (this is discussed in detail in Section 2 and 3 of this report). Most SCW installations have been in regions that also have good water quality. This has enabled the ground-water to be directly circulated through the heat pump. Applications also exist in areas with poorer water quality. In such situations it is common practice to use an intermediate heat exchanger between the well and the heat pump in order to avoid heat exchanger fouling problems.

Historically 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 is focused on heat extraction capacity. In the case of heat extraction from the well

(especially with lower mean ground temperatures) attention has to be paid to the possibility of freezing the well at peak extraction rates.

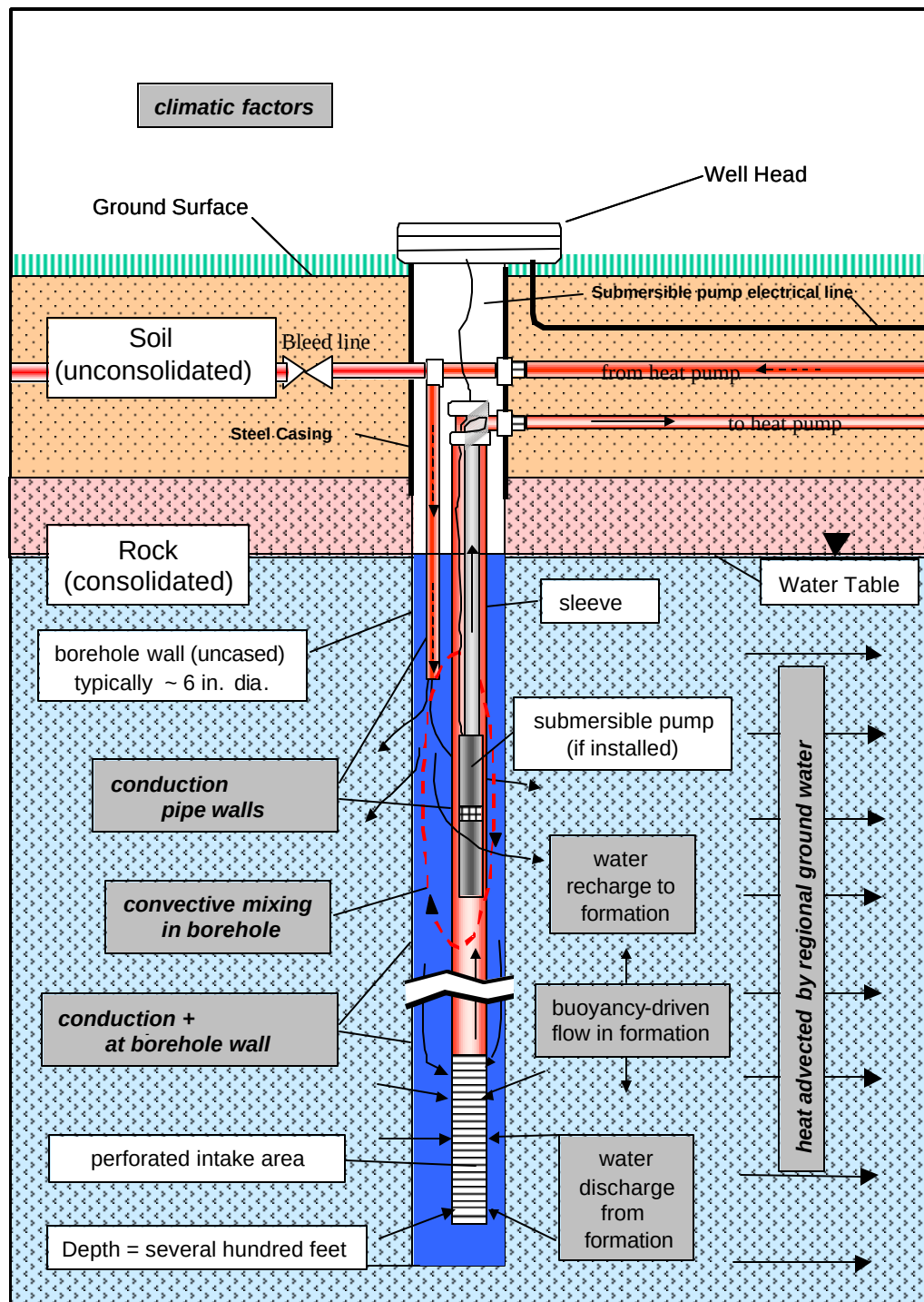


Figure 1.1: Diagram of a typical standing column well system.

If freezing of the well is a concern then 'bleeding' the well can be used to moderate peak temperature swings. In the bleeding process some fraction of the system flow is diverted to another heat sink (or just disposed of) and the flow returning to the well is reduced. This has the effect of drawing more ground-water into the well from further away to make up the flow. This always has the effect of moderating the well temperature. Bleed can similarly be used to lower the peak temperature in heat rejection mode if necessary. If the well is also used for domestic purposes (purely water extraction) this effectively bleeds the system.

The combination of relatively shallow water table and a deep well (some times greater than 1000ft or 300m) means that the well has a large water volume, about 150 gal per 100ft (1800 L/100m) for a 6 in. (0.1524m) nominal diameter well (Sachs & Dinse 2000). Based on experience by the Water and Energy Systems Corporation (Orio, 1994), 50 to 60 feet of water column is needed per ton of building load (4.3m/kW to 5.3m/kW [4.2 to 5.0 ft/(kBtu/hr)]).

1.1 Previous Work

Although there are hundreds (possibly thousands) of standing column well installations in North America there has been relatively little research into their design and performance and only a small amount of literature is available. In this section of the report the significant previous relating to standing column wells is reviewed.

Oliver and Braud (1981) made a steady-state analysis of heat exchange in a well with concentric pipes and derived governing equations for fluid temperature distribution. They derived a closed-form analytical solution for the concentric vertical, ground-coupled heat exchanger under steady-state operation by assuming an isothermal ground surface 10 m [33 ft] away from the center of the heat exchanger. Temperature difference between fluid in the annular area and the earth is the driving force for the heat transfer to the earth mass and the temperature difference in the two pipes is the driving force for the crossover heat flow. The heat exchanger arrangement used by Oliver and Braud is illustrated in Figure 1.2.

Oliver and Braund's analysis assumed steady-state radial heat flow only. They didn't account for the effect of ground water or vertical heat transfer in the rock. Their analysis is based on the following assumptions:

- ? all physical parameters are independent of time, location, pressure and temperature
- ? all heat flow is radial in the heat exchanger;
- ? the only mechanism for heat transfer is conduction
- ? temperature in the flowing fluid is constant at each cross section.

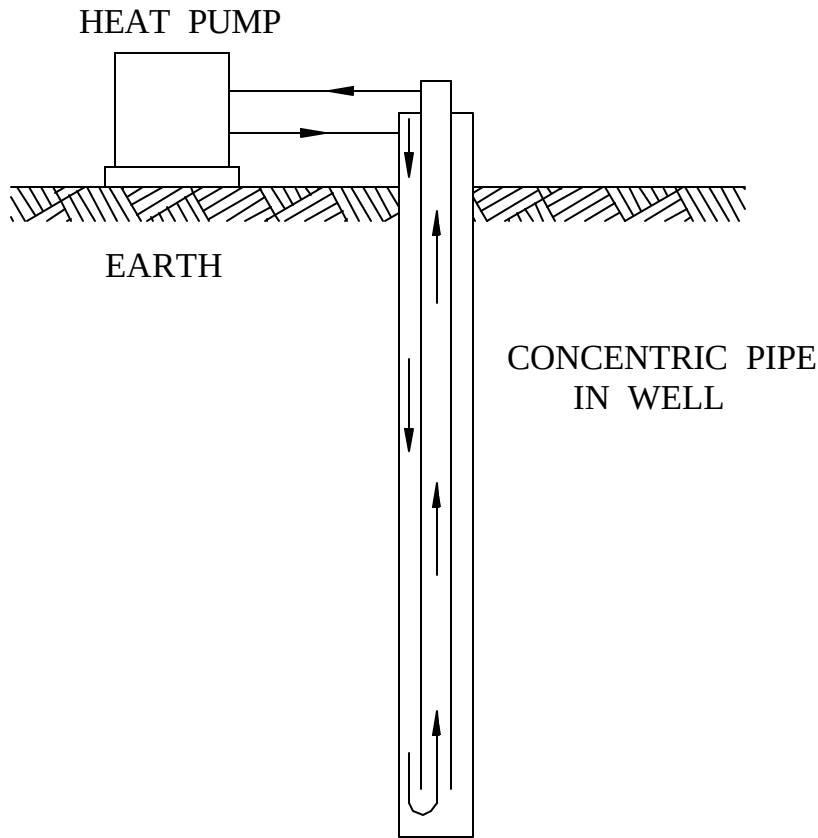


Figure 1.2: Concentric well pipes for thermal exchange to earth with liquid source heat pump (Oliver and Braud 1981)

They derived differential equations from the standpoint of conservation of energy for a control volume of fluid and solved them by analytical methods. The general solution is given by:

$$TR(Z) = \frac{q_2(Z)}{q_1(Z)} = \frac{(l_1 + 1)\exp\{l_1 Z\} - \frac{l_1}{l_2}(l_2 + 1)\exp\{l_2 Z\}}{\exp\{l_1 Z\} - \frac{l_1}{l_2}\exp\{l_2 Z\}} \quad (1.1)$$

where,

$$q_1 = T_1 - T_0;$$

$$q_2 = T_2 - T_0;$$

$$Z = \frac{U_{21}x}{\dot{m}C};$$

$$b = \frac{U_{02}}{U_{21}};$$

x the coordinate of position along axis of heat exchanger well, $x=0$ at the bottom of well; (m [ft]);

T_0 is earth temperature ($^{\circ}\text{C}$ [$^{\circ}\text{F}$]),

T_1 is temperature of fluid in inner return pipe at position x ($^{\circ}\text{C}$ [$^{\circ}\text{F}$]);

T_2 is temperature of fluid in annular area at position x ($^{\circ}\text{C}$ [$^{\circ}\text{F}$]);

$\dot{m}$ is fluid circulation rate (kg/s [lbm/hr]);

C is specific heat (J/kg-K [Btu/lbm-F]);

U_{21} is fluid to fluid conductance of inner pipe (W/m-K [Btu/hr-ft-F]);

U_{02} is conductance of well casing plus earth cylinder, includes film coefficient if appropriate (W/m-K [Btu/hr-ft-F]);

l_1, l_2 are functions of b .

In residential heating and cooling use, the operation of heat pump is cyclic; the energy exchange to earth is highly transient rather than steady state. The steady state value from Oliver and Braud's model (1981) underestimates the heat transfer during the whole year cyclic operation. Moreover, the model does not take into account the beneficial effect of the ground-water flow and the effects of bleed cannot be considered. The model is therefore inadequate for the purposes of this study.

Braud et al. (1983) measured the heat exchange rate of earth-coupled concentric pipe heat exchangers at Louisiana State University. They noted greater conductance values of the concentric pipes over the single U-tubes when concentric heat exchanger was consisted of a steel outer casing (rather than PVC) and PVC inner pipes. Some thermal "short-circuiting" could occur between the inner and outer flow channel, but this can be reduced with use of a low thermal conductivity inner pipe.

Tan and Kush (1986) used a 152 mm (6 in.) diameter, 189 m (620ft) deep standing column well located at Westchester County, NY, in their study. They called the SCW a "semi-closed loop" because of the influx/outflow of ground water at fissures in the rock. Water was withdrawn at a depth of 12.2 m (40 ft) and the return water from the heat pump was re-injected at a depth of 183 m (600 ft). The fluid water flow rate was 0.6935 kg/s (11 gpm) with a 0.25kW (1/3 hp) circulating pump at the ground level outside the well. The static water table level was at a depth of 1.52 m (5 ft). Water was discharged to the bottom of the well, thus the water supplied to the heat pump does not pass through the region of discharge. So some insulation on the tubes can be avoided in this case. The parameters about well, heat pump and system were thoroughly measured and documented for a continuous 22-month period in this field test project.

Tan and Kush (1986) measured the entering water temperature to the heat pump and found it ranged from 6.9 $^{\circ}\text{C}$ (44.5 $^{\circ}\text{F}$) in early January to slightly over 15.6 $^{\circ}\text{C}$ (60 $^{\circ}\text{F}$) in mid-July of the second cooling season. According to their field test, Tan and Kush (1986) concluded that SCW systems could give very stable EWT to the heat pump even in severe winter or summer. In their test, the lower limit for the heat pump operation, which was set at leaving water temperature of 38 $^{\circ}\text{F}$ (3.33 $^{\circ}\text{C}$), was never reached.

Regarding the influence of ground water, if the well is uncased, the local hydrology will affect the performance of the well. Although in their test, this effect was not quantified,

Tan and Kush(1986) pointed out that substantial infiltration/exfiltration can enhance the system performance greatly. No information about bleed was found in Tan and Kush's research.

Yuill and Mikler (Mikler, 1993; Yuill and Mikler,1995) used a well at Penn State University to research the performance of standing column well systems. They referred the standing column well as a "thermal well". The thermal well serves as a circulation, withdrawal and injection well at the same time. The system is shown in Figure 1.3. They developed a simplified mathematical model to describe the coupled thermo-hydraulic energy transfer by conduction and convection in an aquifer surrounding a thermal well. A schematic of the well system is shown in Figure 1.3.

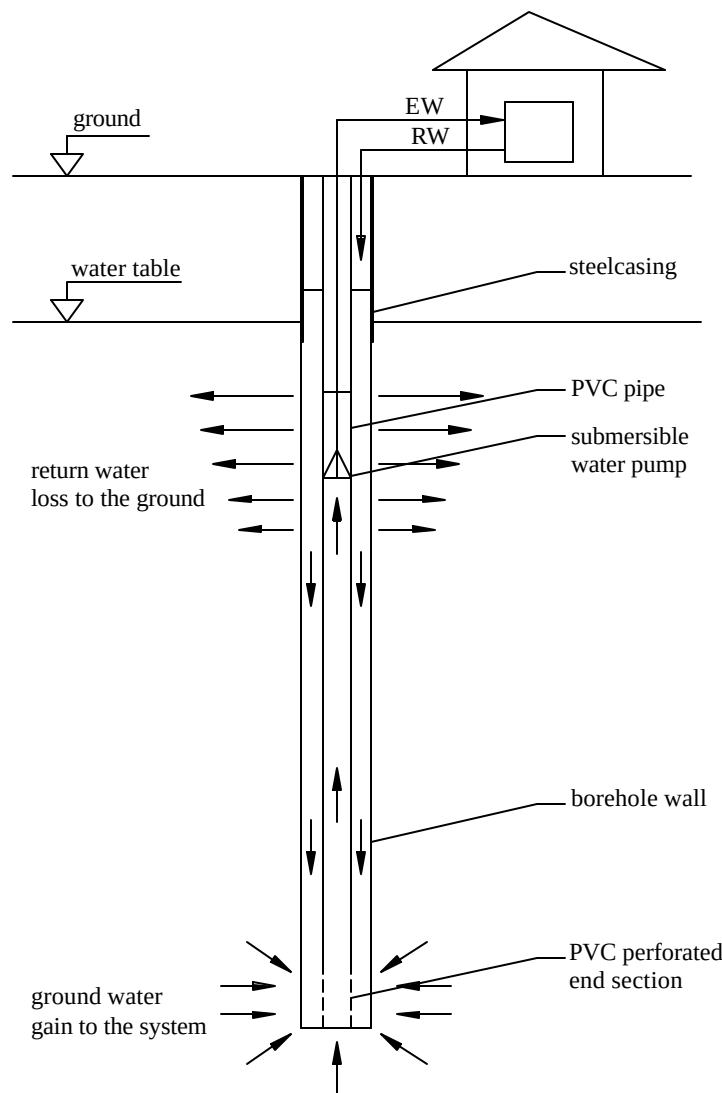


Figure 1.3: Schematic of the 'thermal well' studied by Yuill and Mikler (1995).

To simplify the analysis, Yuill and Mikler used the following assumptions:

- homogeneous and isotropic aquifer
- cylindrical symmetry of the coupled flow around the axis of the borehole
- no heat or ground water flow in the vertical direction
- laminar ground water
- no dispersion (no groundwater diverted to other places)
- thermal well is in the dynamic hydraulic equilibrium with the surrounding groundwater aquifer
- natural hydraulic gradients in the aquifer are neglected; hydraulic gradients caused by pumping are dominant.

Based on these assumptions and by introduction of “groundwater factor” (G_f), which is the ratio of convection to conduction, the governing partial differential equation was derived from energy conservation simplified and solved numerically.

$$\frac{\partial^2 T}{\partial r^2} + \left[\frac{1 \pm G_f}{r} \right] \frac{\partial T}{\partial r} = \frac{1}{a} \frac{\partial T}{\partial t} \quad (1.2)$$

Where G_f is groundwater factor,

$$G_f = \frac{\dot{m}_w C_{pw}}{2p \cdot k \cdot dz};$$

$\dot{m}_w$ is groundwater mass flow rate, either discharge groundwater or suction groundwater flow.(kg/s [lbm/hr]);

C_{pw} is specific heat of water (J/kg.K [Btu/lbm. °F]);

k is thermal conductivity of the ground(W/m.K [Btu/hr.ft.°F]);

a is Thermal diffusivity of the ground (m²/s [ft²/hr]);

z is vertical coordinate(m [ft]).

The governing equations are converted into explicit forms of finite difference equations by using central difference approximations. Also, Yuill and Mikler (1995) introduced a new term, equivalent thermal conductivity (k_{eq}), to account for the improved heat transfer due to the induced groundwater flow in the aquifer. In order to get the value of k_{eq} , they let heat transfer rates along the borehole wall for the case of coupled thermo-hydraulic flow considering the real ground thermal conductivity (k) equal to the ones for the case of pure heat conduction. They suggested this equivalent thermal conductivity could be used in the existing pure heat conduction design models to determine the depth of the thermal well.

Yuill and Mikler (1995) used a steady-state solution of the hydraulic head distribution in the thermal well model. They assumed that the hydraulic gradients caused by pumping are dominant with respect to natural hydraulic gradients in the aquifers. Therefore, during their analysis, they neglected the natural hydraulic gradients. The equilibrium well equation relating the groundwater flow rates to the hydraulic gradients in the well was given by:

$$Q_w = -\frac{2p \cdot K \cdot \Delta h \cdot dz}{\ln(R/r_b)} \quad (1.4)$$

where, Q_w is water flow rate (m^3/s [gpm]);

K is the hydraulic conductivity of the ground (m/s [gpd/ft²]);

R is radius of influence (m [ft]);

r_b is borehole radius (m [ft]).

This constant head distribution was then used in the thermal model. The finite difference model allowed calculation of the radial heat transfer at a particular depth but was not truly two-dimensional. Consequently vertical heat transfer, end effects and bleed operation could not be considered.

According to their research, the required drilled depth of a 6-in thermal well is about 60% of the depth of the 1^{1/2}-in, U-tube earth-coupled borehole, assuming that both are properly designed and are installed in the same geological formation. Yuill and Mikler concluded that properly designed and installed “thermal wells” could compete with any of the closed-loop systems based on their high system performance with smallest borehole depth and lowest combination of installation and operating costs.

Orio (1994,1995) has used the Kelvin line theorem to analyze the heat transfer in standing column well systems.

$$T - T_0 = \frac{Q'}{2pk_s} \int_X^\infty \frac{e^{-B^2}}{B} dB = \frac{Q'}{2pk_s} I(X) \quad (1.5)$$

$$X = \frac{r}{2\sqrt{at}}$$

where, T is soil temperature (F [°C]);

T_0 is initial temperature of the soil (F [°C]);

Q' is heat transfer rate, negative for heat extraction and positive for heat rejection (Btu/ft-hr [W/m]);

r is radial distance from line (ft [m]);

k_s is thermal conductivity of soil (Btu/hr-ft-F [W/m-C]);

a is thermal diffusivity (ft²/hr [m²/s]);

t is heat pump run time-hours;

B is integration variable.

According to Orio (1995) research, the results of the Kelvin line theorem provide a good correlation between the theory and some practical field experience. The results of this model were also compared with the model developed by Braud (1983). The correlation between these two models was within one degree Celsius for the evaluated examples. Clearly this model does not allow for consideration of any ground-water flow directly and can not be used to calculate the effects of bleed.

Orio also gives some practical data on SCW systems and bleed practices. It is reported that in the severity of winter or summer, a relatively small, e.g. 10% bleed, can reestablish water temperature in the well of SCW system at a rapid rate. According to their observations the bleed can make the effective thermal conductivity increase by factors of 3 to 5. The homogeneity of the geologic formation, the characteristics of the aquifer and the density of the fractures affect the performance of the SCW systems with bleed. Usually, 80-90% of the water is returned to the standing column well and the balance is returned to earth some distance away or disposed of. National Ground Water Association (NGWA) provides the following formula to calculate the optimum returned well distance:

$$D = \sqrt{0.2 \times Q} \quad (1.6)$$

Where D is the distance in feet to the recharge well (ft [m]);
 Q is design heat transfer rate (Btu/hr [W]) .

Orio (1999) discussed the placement of pumps and the depth of the boreholes. The boreholes could be one-half the depth of the closed loop earth coupling methods. When boreholes get deeper than 150m (500 ft), there is substantial increase in heating energy because the earth temperature increases with the increasing depth. But, placing the pump at the bottom of the borehole has some disadvantages such as future service and installation cost. To eliminate these disadvantages, Orio (1999) proposed that the submersible pump should be placed at the top of the borehole, but with a lightweight plastic tube inserted to the bottom of the borehole (Figure 1.4 b). Thus, the most stable water temperature is achieved, and shorter pipes and wires are required and the initial investment can be reduced. Deeper wells (depth >150m [500 ft]) mostly use dip tubes constructed of 100mm (4in) diameter PVC pipe to the bottom of the well. The dip tube has a minimum of 120 one-inch perforations in the lowest 12m (40 ft).

An open loop concentric well heat exchanger called a “Geohill” has been developed by Geocalor A.G (Hopkirk & Burkart 1990). The system schematic is shown in figure 1.5. The borehole is 250mm (10in) in diameter up to 300m (1000ft) deep and it remains open apart from a steel casing in the upper part. A central PVC tube is surrounded by graded gravel filling and contains a down-hole pump feeding water via an insulated tube to the heat pump. The fluid return is through the gravel-filled annulus. According to this configuration, the gravel filling can increase friction resistance for the return water flowing down and therefore more groundwater is sucked into the system, especially if the well is drilled in a highly permeable rock formation.

According to Hopkirk & Burkart ‘s research (1990) , the “GEOHILL” system shows much promise, especially in larger commercial installations requiring both heating and cooling.

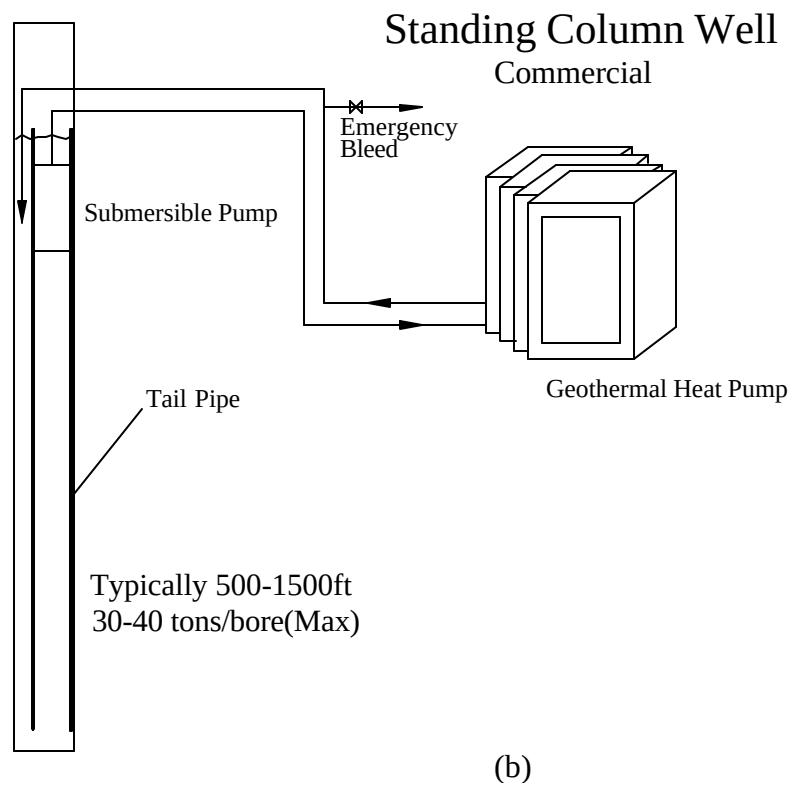
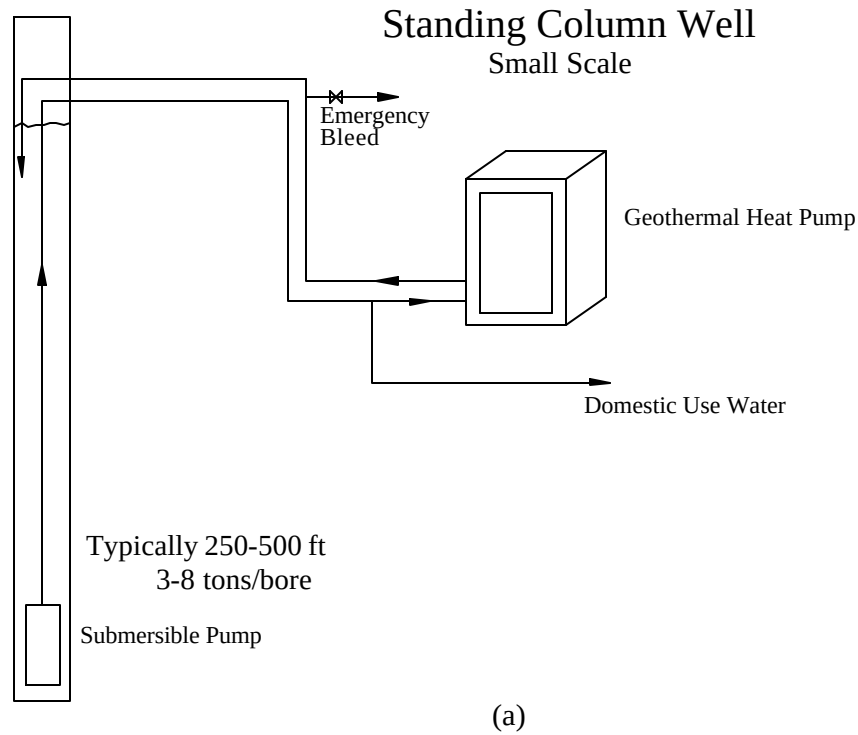


Figure 1.4: Schematics of standing column well from description of Orio (1999).

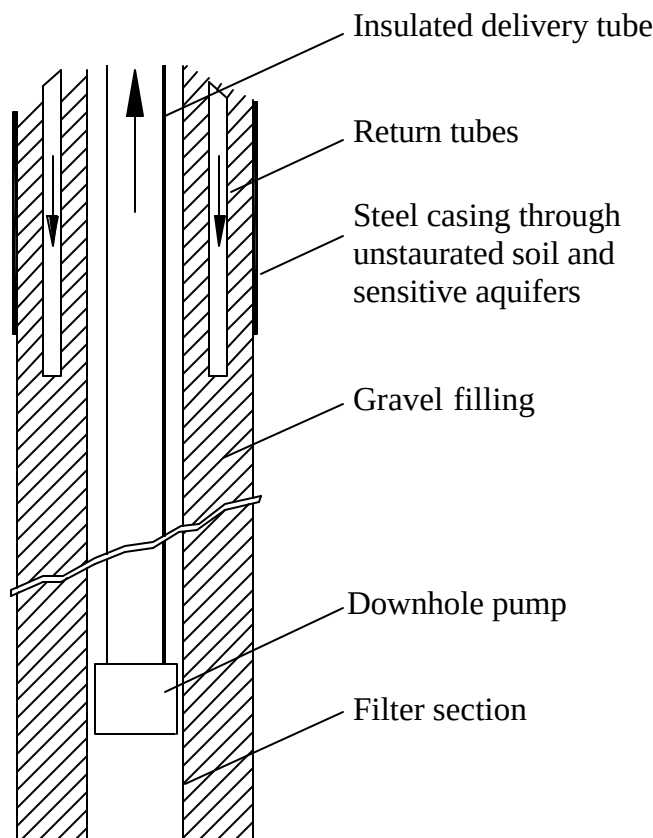


Figure 1.5: Diagram of a 'GEOHILL' open hole coaxial thermal well (Hopkirk & Burkart 1990).

1.2 Objectives and Approach

The application of Geothermal heat pumps has been growing at a rapid pace for the last several decades due to the systems economic, environmental, aesthetic and comfort advantages over other HVAC systems. This trend is expected to continue in the future as a result of strong support by governmental agencies at all levels as a reflection of wide community support and acceptance. Although it has been stated that over one thousand installations exist, these have mostly been designed on a heuristic basis using knowledge of what has worked in similar geological and load conditions.

From the review of the literature discussed in Section 1.1 it is clear that research into the operation and design of standing column well systems has been very limited. To date no models have been developed that have come into common use in design procedures for such systems. Attempts have been made to adapt conduction heat transfer models to include effects of ground-water flow. However, these models and more sophisticated models (e.g. Yuill and Mikler, 1995) do not allow the representation of bleed from the well. As this is common practice and can have a significant effect on the design and cost of the well there is a clear need to be able to model this effect.

The overall objective of this project was given as ‘to systematically study the characteristics of standing column wells in order to establish firm guidelines for site selection, necessary well length per given load, and preferred designs and strategies’.

Our approach can be defined in terms of four main tasks. These have been:

Task1: Compile and analyze field data.

Task2: Develop a numerical model of a standing column well system

Task3: Conduct a parametric study using the numerical model and examine the effects of key design parameters on SCW performance

Task4: Documentation and report writing

The tasks are each discussed in the following subsections.

1.2.1 Task 1: Compilation and Analysis of Field Data

This task has been primarily conducted by Water and Energy Systems Corporation. This task has involved collecting data on existing installations by a process of examining well logs, sending questionnaires to drillers and contractors and making personal contacts. The objective has been to collect the following types of data:

- Standing column well construction
 - Well depth and diameter
 - Drilling conditions
 - Pump and pipe arrangement
- Local climate and hydrological and geological conditions
- Operating strategies and characteristics
- Recorded operating data for model validation and case study.

In addition to collecting field data of this type existing sources have been used to collect information regarding North American geological and Hydrogeological conditions, particularly for regions known to include SCW installations.

1.2.2 Task 2: Mathematical and Computer Modeling

The heat transfer and hydrological boundary conditions in this type of problem vary in both time and space and also depend on the mode of operation of the well. The full complexity of the boundary conditions associated with standing column well operation can only be dealt with by a ground-water flow and heat transfer numerical model. Sophisticated numerical models of ground-water flow and contaminant transport in both the saturated zones (rock) and unsaturated zones (soil) have been developed over the last two decades. These models have been applied by practicing hydrogeologists to study large-scale water supply and contaminant transport problems. The project team has recently reviewed many of the available commercial ground-water flow modeling codes in studying the effects of ground water flow on closed-loop heat exchangers (Chiaasson et

al., 2000). This showed that although such codes deal effectively with modeling the pumping process and calculation of ground-water flow, they are not adapted to enable the complex time varying thermal boundary conditions required to model a SCW system over an extended simulation period.

The approach to developing a suitable numerical model has been to use an existing finite volume code (developed at OSU) and couple this to a detailed thermal model of the borehole. This enables the coupling of the ground-water flow and heat transfer around the well to be accounted for. Modeling the coupled flow and heat transfer processes in this way allows bleed processes to be included in the study. Using a detailed thermal model of the borehole allows study of the associated design parameters such as dip tube size, insulation, borehole surface roughness etc. The flexible structure of the code allows time varying bleed rates and building loads to be included in the model.

1.2.3 Task 3: Parametric Study

Task 3 is a parametric study to determine the effect of key parameters on the performance of SCW systems. To accomplish this task, one or more years of hourly building loads from a prototype building have been used to provide thermal boundary conditions for the model(s) developed in Task 2. 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-off” times.

The parametric study has been organized using a ‘base case’ and calculating the system performance for this and other cases where a single parameter variation 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
- Borehole depth
- Rock hydraulic conductivity

Results of the parametric study have been used to examine which are the most significant parameters affecting the SCW design. Calculations with differing well depths enable each parameter variation to be correlated with potential reduction/extension of borehole depth.

2.0 Survey of Standing Column Well Installations

The objective of this study has been to catalog a representative group of SCW locations, designs and operating practices. Several sites were to be identified for instrumentation to validate computer models. This information could be used to aid in setting direction for developing formal design procedures to be published in the ASHRAE Handbook.

The objective has been to collect the following types of data:

- Standing column well construction
 - Well depth and diameter
 - Drilling conditions
 - Pump and pipe arrangement
- Local climate and hydrological and geological conditions
- Operating strategies and characteristics
- Recorded operating data for model validation and case study.

The findings reported in this section are mainly from the results of a questionnaire sent out to contractors and drillers by Water Energy Systems Corp. The letter sent out, and an example of the questionnaire is given in Appendix A.

In the Northeast heating requirements generally dominate residential applications while some commercial office buildings might approach cooling dominant conditions. As a result the discussion that follows will assume a heating load in all cases with the realization that cooling is also a factor.

2.1 SCW Installation Survey Findings

2.1.1 Local Climate

All of the sites surveyed in this report are in New England /New York and have heating dominated loads. Typically 2200-2500 hours of heating and 600-800 hours of cooling are required annually

2.1.2 Well Data

Data from 34 wells at 21 locations have been collected and are believed to be representative of current installation practice and geographical distribution. Eleven residences and ten commercial/school buildings are included in the study. Samples are located in New England and New York. Massachusetts leads the list with 10 sites. A summary of the data is given in Table 2.1. The raw data collected is shown in Tables 2.2-2.6.

R&D Studies applied to SCW design

Survey of SCW Installations

Table 2.1
Summary of collected Well Data

	Residential		Commercial	
	Range	Mean	Range	Mean
Installed Capacity (Tons)	5-15	7.7	10-100	57
Well Depth (Ft.)	240-900	518	600-1500	1238
Depth/Capacity (Ft/Ton)	32.2-85	59	30-65.5	49
Static Water Level. (Ft.)	3-120	48	16-40	20

Table 2.2
Standing column well field data

Site		New England Quilt Museum Lowell, MA	Hastings School Westborough, MA	Sherwood Forest Apts Saugus, MA	Halibut Point State Park Rockport, MA
	Units				
System Capacity	Tons	60	200	63	6.5
No. of Wells		2	6	4	1
Depth	Feet	1040/855	1500	3@1100,650	480
Location of Pump	Feet	50	110	50	100
Length/Capacity	Feet/Ton	30	44	59.5	65.5
Diameter of Wells	Inches	6		6	6
Static Water Level	Feet	20	6-10	20/25	29
TTL Yield/Drawdown	GPM/Ft	75	7-100	1.5/4	
Depth to Bedrock	Feet	25-28	82 -85	10/31	
Depth/Type of Rock				Lt/Dk Grey Bedrock	
Depth/Type of Rock					
Well Pump Mfr.		Meyers	Meyers	Goulds	Goulds
Well Pump Model		J5080	J5080	35LD20	18GS07
Well Pump HP		5 HP	5 HP	2 HP	3/4 HP
Well HP/Ton		0.167	0.15	0.095	0.11
Well Log?		yes	Yes		yes

R&D Studies applied to SCW design

Survey of SCW Installations

Table 2.3
 Standing column well field data

Site	Units	Blackpoint Inn Main #2 Scarborough, ME	Haverhill Library Haverhill, MA	Maine Audubon Falmouth, ME	Hanscom AFB Bedford, MA
System Capacity	Tons	38.5	110	15	10
No. of Wells		1	4	1	1
Depth	Feet	1500	1500	600	650
Location of Pump	Feet	120		100	50
Length/Capacity	Feet/Ton	37.9	53.3	36.7	59.5
Diameter of Wells	Inches	6	6	6	6
Static Water Level	Feet	10	40	25	10
TTL Yield/Drawdown	GPM/Ft	15	7/15		30
Depth to Bedrock	Feet	11	22/23		30
Depth/Type of Rock		<11, clay, gravel			clay 20/30
Depth/Type of Rock		>9, bedrock			>30 med gray
Well Pump Mfr..		3/5 HP	Meyers	Webtrol	Goulds
Well Pump Model			J5090	352S2012	25GS10
Well Pump HP			5 HP	2 HP	1 HP
Well HP/Ton		0.08	0.18	0.13	0.1
Well Log?		yes	yes	no	yes

R&D Studies applied to SCW design

Survey of SCW Installations

Table 2.4
Summary of standing column well field data

Site	Units	Appleton St Apartments Cambridge, MA	Residence Raymond, ME	Residence Uxbridge, MA	Residence Raymond, ME
System Capacity	Tons	10	7	5	10
No. of Wells		1	1	1	1
Depth	Feet	650	750	240	520
Location of Pump	Feet	50	100	220	60
Length/Capacity	Feet/Ton	59.5	85	39	50.5
Diameter of Wells	Inches	6	6	6	6
Static Water Level	Feet	30		20	15
TTL Yield/Drawdown	GPM/Ft	6	8	5	50
Depth to Bedrock	Feet	70			
Depth/Type of Rock		>70 med gray			
Depth/Type of Rock					
Well Pump(s) Descr.		Grundfos		Goulds	Goulds
Well Pump Model		25GS10-7		13GS10	40GS30
Well Pump HP		1 HP		1 HP	3 HP
Well HP/Ton		0.1		0.2	0.3
Well Log?		yes		no	yes

R&D Studies applied to SCW design

Survey of SCW Installations

Table 2.5
Summary of standing column well field data

Site	Units	Residence Carlisle, MA	Residence Okimo Mt VT	Residence N. Easton, MA	Residence Windham, NH
System Capacity	Tons	6	15	5	7.5
No. of Wells		1	1	1	1
Depth	Feet	425	900	460	545
Location of Pump	Feet	75	75	420	525
Length/Capacity	Feet/Ton	60.8	55	77	54.8
Diameter of Wells	Inches	6	6	6	6
Static Water Level	Feet	35	50	50	109
TTL Yield/Drawdown	GPM/Ft				27/122
Depth to Bedrock	Feet				
Depth/Type of Rock					
Depth/Type of Rock					
Well Pump(s) Descr.		Goulds	Grundfos	Goulds	
Well Pump Model		25GS20	40GS20432	118G507	
Well Pump HP		2 HP	2HP	3/4 HP	
Well HP/Ton		0.33	0.13	0.15	
Well Log?		no	no	yes` no Porter	no Porter

Table 2.6
Standing column well field data

Site	Units	Blackpoint Inn Cottages Scarborough, ME	Blackpoint Inn Main #1 Scarborough, ME	Residence Rye, NH	Res. Tapsham, ME
System Capacity	Tons	26.5	200	10	5
No. of Wells		1	4	1	1
Depth	Feet	1500	1500	350	510
Location of Pump	Feet	220	120	25	490
Length/Capacity	Feet/Ton	55.0	37.5	32.2	73
Diameter of Wells	Inches	6	6	6	6
Static Water Level	Feet	15	15	3	120
TTL Yield/Drawdown	GPM/Ft	12	30	30/0	1/120
Depth to Bedrock	Feet	11	9		
Depth/Type of Rock		<11, clay, gravel	<9, clay, gravel		
Depth/Type of Rock		>11, bedrock	>9, bedrock		
Well Pump Mfr..		5/5 HP	3/5 HP		
Well Pump Model					
Well Pump HP					
Well HP/Ton		0.19	0.08		
Well Log?		yes	yes	no	

2.1.3 SCW Construction

Well diameters are generally 6 inches in bedrock with 8 inch steel casing transitioning from the surface into the bedrock. Construction differences existing in the reported standing column wells relate in part to the depth of the well rather than any other influencing parameter. Shallower wells (i.e. depths less than 150m [500 ft.]) tend to be dominated by placement of the pump near the bottom of the well with the return located near the top. Deeper wells (depth greater than 150m [500 ft.]) mostly use dip tubes (Porter Shroud) constructed of 100mm (4 in.) diameter PVC pipe to the bottom of the well. These dip tubes have a minimum of 120 one inch perforations at 6 to 12m (20 to 40 f.) from the bottom. The pump and return pipe end are located near the top of the well taking into account draw-down depths at bleed flow rates of from 5% to 25% of total heat pump flow depending on the application. The return pipe end is positioned to be below the static level at all operating conditions. The pump is positioned to have the required NSPH at all operating conditions including at higher temperatures in cooling.

Supply and return lines are sized to approximately 1.5m/s (5 ft./s) to minimize flow noise and friction pressure drop. It is customary practice to insulate the supply and return lines with a single layer of polystyrene foam between them and the pair buried in 125-150mm (5-6 in.) of sand. A double pit-less adapter is employed to allow easy removal of the pump for periodic inspection.

A conventional submersible well pump of sufficient capacity to provide the water source heat pumps 3 GPM/Ton at a head that encompasses the static head under operating conditions, pipe valve and fitting losses and the pressure provided to the heat pumps (usually 135kPa [20 psig]).

Many residential applications utilize the standing column well for domestic water supply purposes as well as geo source water for heat pump operation. This generally involves the management of a two-pressure system and is often equipped with a variable speed driven submersible well pump.

2.1.4 Operating Strategies and Characteristics

An open well design requires careful analysis and management of the water flow from the pump through the heat pump and back to the well. Pumping energy is minimized if water flow and pressure are managed to the lowest values required. Self regulating flow control valves are recommended and used on most sites minimizing the requirement for individually flow balancing the equipment.

Especially important for automatic operation of the system is the correct specification of bleed flow. Bleed flow is used in cases of maximum heating load for those wells identified with higher yields permitting lower first cost by reducing well length per ton. Models are used to predict the safe amount of bleed flow to prevent equipment freeze-up but often depend on estimated geological parameters. Measuring the well temperature drop while running continuously for an extended period of time with a specific bleed rate yields useful data to back up the model.

2.1.5 Bleed Flow

In colder climates such as New England, where heating represents the dominant comfort conditioning load, and lower groundwater temperatures prevail, the use of a predetermined small bleed flow (over flow) rate to increase well water temperature on command by convective groundwater flow is often essential and can save the owner drilling costs. On design or near design days the heat pumps can run at full capacity for as much as 20-24 hours continuously. To prevent extreme water temperature depression and consequent heat exchanger freezing, a bleed flow of well water can be called into function to re-stabilize the source water to a higher temperature. Heretofore the determination of bleed rates has been empirical but effective. The results of the survey point to the fact that these small bleed rates can be more accurately set by design based on well yield and depth/capacity ratio. The validation of that algorithm would allow a more accurate estimate of the beneficial effect of higher or lower bleed rates.

2.1.6 Multiple Standing Column Well Systems

Some large systems, greater than 30 Tons, require more than one standing column well to achieve the required ground heat exchange. These larger systems will employ multiple heat pumps, zoned or staged in a diversified manner. The most efficient design of geo water supply employs variable speed technology to control the pressure at the inlet of the heat pumps.

Single well systems return the water to the well at the same volume pumped out thus maintaining the water level in the well constant. Not so in multiple well systems. Even careful design and balancing will not return precisely the same volume as was removed. Most multiple well systems are now arranged so that the pumps are powered from individual Variable Speed Drives in Master/Slave arrangement to drive all pumps with the same frequency and nearly the same flow. Returning equal flow volumes requires measuring supply and return flows at N-1 wells, where N is the total number of wells, and carefully throttling individual returns. With automatic flow control valves on the heat pumps, their nameplate control settings can be used to estimate the total flow.

However most wells will absorb some overflow so a minor mismatch will not be a problem especially with deeper wells.

If it were not for the significant unequal return flow volumes, multiple well systems could easily be operated with one well driven from a VSD while the others cut in and out using inexpensive pressure switches. This problem can be overcome by the use of a crossover pipe connecting the wells if the wells are at the same elevation within one foot and the crossover is located at a depth of 6 feet or more.

2.2 Installations with detailed operating data

2.2.1 Maine Audubon Visitor's Center

Installed in 1996, this 520m² (5400 sq. ft.) building has 52.8kW (15 Tons) of water to water heat pumps delivering to radiant floors and fan coils throughout the building. The three heat pumps source from a single 180m (600 ft.) standing column well. At its inception the well pump was controlled by a pressure switch and fed a pair of large accumulator tanks to minimize cycling. A constant (with HP's running) bleed to a duck pond of unknown quantity was used.

In the winter of 1999/2000 the system was upgraded to incorporate a VSD on the well pump, building water temperature reset, and an automatic bleed system in an effort to increase efficiency. The automatic bleed system installed was found to be inadequate due to excessive resistance to flow caused by an overly restrictive solenoid valve and spring loaded flowmeter. The constant bleed was restored and set at about 33% flow (0.85L/s [13.5 gpm] under max load conditions). No problems have been reported relating to dangerously low well water temperatures. In mid-March, 2001 after a full season, the well water temperature was 9.4-10°C (49°F -50°F) while in January readings of 6.1-7.8°C (43°F – 46°F) were recorded indicating the bleed could have been set somewhat lower but at this site it is not a problem since water run off promotes wildlife activity in the immediate area, a desirable side benefit.

2.2.2 Residence Raymond, ME

This building is a 370m² (4000 sq. ft.) residence with seven tons of heat pump capacity (Logan, 2001). The resident is on a time of day electric utility rate system \$0.26/KWh weekdays from 7 am to Noon and 4pm to 8pm and all other times at \$.05/KWh. A timer locks out the heat pumps during peak rate times. This is possible due to the higher

thermal mass of the floor radiant heating system. A schematic diagram of the system is shown in Figure 2.2.

The standing column well is 213m (700 ft) deep with an effective length of 180m (600 ft.) or approximately 7.4m/kW (85 ft./ton.) The bleed is set to 4.8% (0.063 L/s [1 GPM]) and is operated by a thermostat with a setting of 5.6°C (42°F) open 8.3 °C (47°F) close. Figure 2.1 shows the well water temperature, outside air temperature and bleed time expressed as a percentage of running time. Data was collected by the resident every Sunday at 7am and 8pm and averaged. Total running time for the system annually in heating is 1800 hours and comparing to normal expected heating hours (2600), the system is about 25% oversized. As can be seen in the figure the heaviest bleed occurs in the three months of January, February and March shouldered by steep ramps of 1.5 months in the fall and 2 months in spring. Total annual bleed flow was calculated to be 340m³ (63,500 gal.) – or about 47m³ (12,500 gal.) per year per load ton

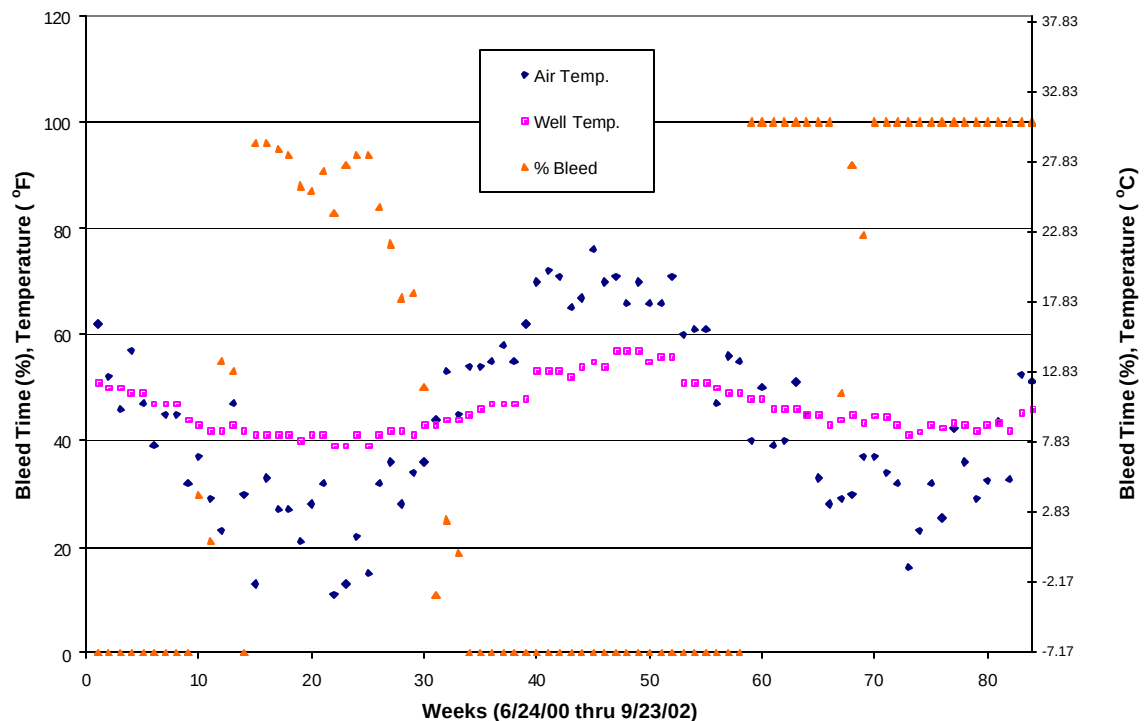


Figure 2.1: Well and air temperatures plotted with percentage time bleed for the residential installation at Raymond, ME.

2.2.3 Hotel, Scarborough, ME

Three buildings containing 150 guest rooms, kitchen, dining rooms and conference meeting rooms with a mixture console and unitary ground source heat pumps. No central DDC control/monitoring system is installed as each unit has it's own thermostat and overall water-flow is regulated on demand by variable speed drives powering the well pumps under PID control at 20 psig pressure. When originally installed the control method sequenced the wells on and off as the demand varied. Difficulty was encountered

managing the return flow to the proper well and some wells were getting more operating time than others. The owner asked to change the control strategy to master-slave – slave driving all wells at the same frequency and nearly the same flows. Once the return flows are balanced they deliver nearly equal flows to each well.

(Open-loop) Geothermal Heat Pump System supplying hydronic radiant floor heating & fan-coil units.

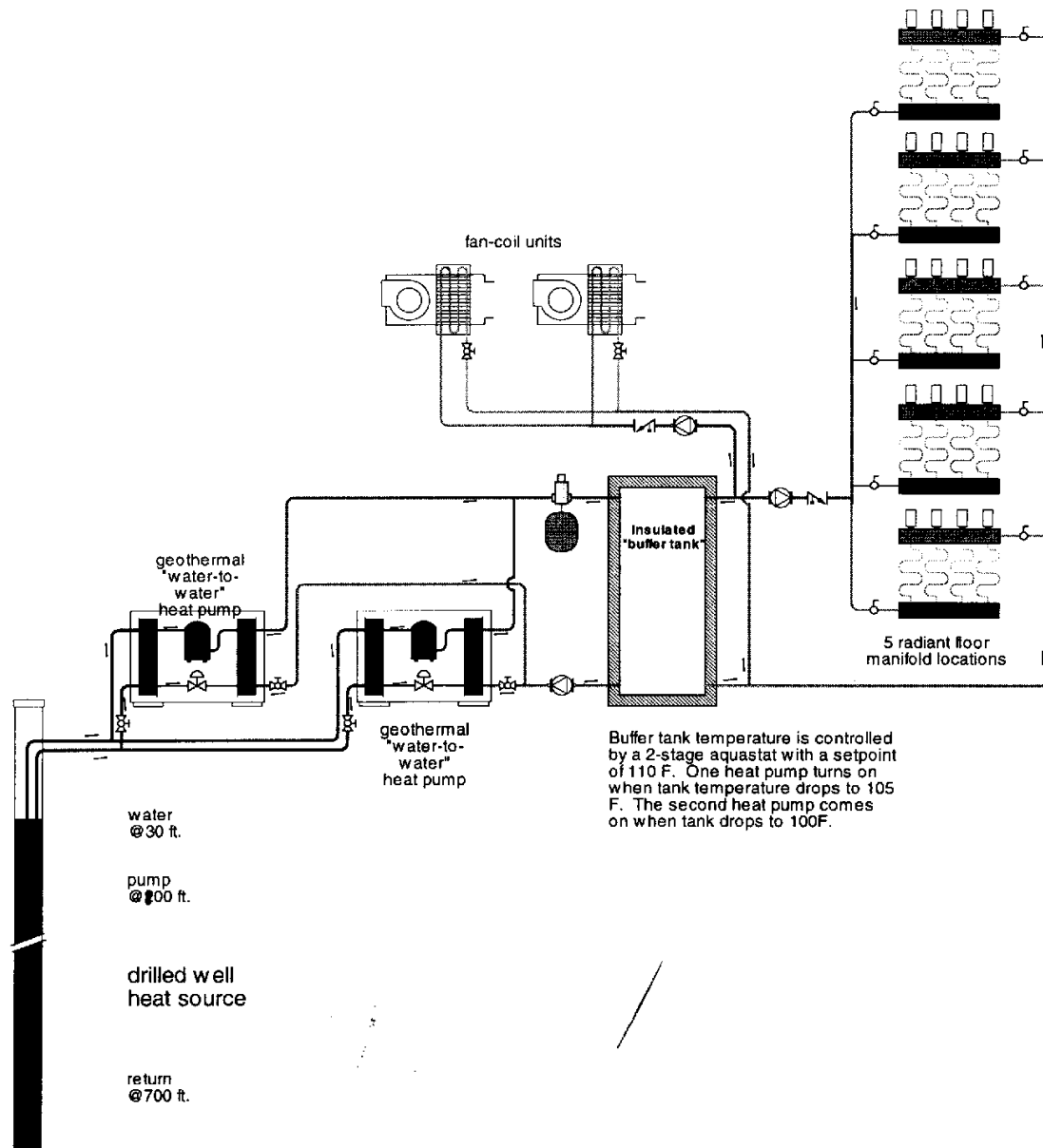


Figure 2.2 A schematic diagram of the standing column well and radiant floor heating system for the residential installation at Raymond, ME.

2.3 Future Installation Monitoring and Characterization

Standing column well performance depends on many factors, some of which are unknown at the time of installation. A suggested test protocol for comparison purposes consists of extracting heat at the design rate for a specific length of time and bleed rate. The well supply water temperature drop is then recorded. After the well is allowed to recover the test is repeated at another bleed rate. Perhaps a third run is made to get a picture of the capability to be compared with computer models and other well data.

The following parameters should become part of any selected residence or commercial application for future monitoring to evaluate design effectiveness.

- Well water temperature – continuously monitor with daily average as well as peak high and lows.
- Well bleed flow – continuously monitor with daily total. Measure initial bleed percentage rate and note any changes in rate.
- Equipment run hours – continuously monitor with daily total. Estimate match to actual load.
- Rock conductivity – Perform during construction phase or estimate from type of rock.
- From National Weather Service obtain data of daily heating and cooling degree-days.

3.0 Geological and Hydrogeological Characteristics of Standing Column Well Installations

In this section, the geologic and Hydrogeological conditions of current and potential SCW installations are described. This section is divided into three subsections. First, an overview of the hydraulic and thermal properties of soils and rocks is presented. Second, the ground-water regions of North America are briefly described, and third, a more detailed discussion of the geologic and Hydrogeological characteristics of the regions where SCWs exist is presented.

3.1 Hydraulic And Thermal Properties Of Soils And Rocks

Underground water occurs in two zones: the unsaturated zone and the saturated zone. The term “ground water” refers to water in the saturated zone. The surface separating the saturated zone from the unsaturated zone is known as the “water table”. At the water table, water in soil or rock openings is at atmospheric pressure. In the saturated zone (below the water table), openings are fully saturated and water exists at pressures greater than atmospheric. In the unsaturated zone, the openings are only partially saturated and the water exists under tension at pressures less than atmospheric.

In the context of SCWs, it is useful to identify the types of openings in geologic materials, as these have an important impact on the heat transfer and fluid flow in the material. Openings formed at the same time the rock or soil is formed are referred to as primary porosity. These include pore spaces in sedimentary deposits as well as lava tubes in volcanic rocks. Openings that develop after a soil or rock is formed are referred to as secondary porosity. These include fractures, joints, and faults in igneous, metamorphic, and sedimentary porosity, and solution cavities in carbonate or other soluble rocks. The types of openings in geologic materials are shown in Figure 3.1.

Ground water is present nearly everywhere, but it is only available in usable quantities in aquifers. An “aquifer” is defined by Driscoll (1986) as a formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield economical quantities of water to wells and springs. Aquifers are described as being either confined or unconfined. Unconfined aquifers are bounded at their upper surface by the water table. Confined aquifers are bounded between two layers of lower permeability materials.

Naturally-occurring ranges of values of hydraulic and thermal properties of soils and rocks are summarized in Table 3.1. These properties can be regarded mainly as functions of mineral content, porosity, and degree of saturation.

Table 3.1
Typical Values of Hydraulic and Thermal Properties of Soils and Rocks

Geologic Material	Hydraulic Properties				Thermal Properties			
	Hydraulic Conductivity* (K)		Porosity* (n)		Thermal Conductivity** (k)		Volumetric Heat Capacity** ($\rho_s c_s$)	
	ft/s (m/s)		(--)		Btu/hr-ft-°F (W/m-°C)		Btu/ft³-°F (J/m³-°C)	
	Range	Geometric Average	Range	Arithmetic Average	Range	Arithmetic Average	Range	Arithmetic Average
Soils								
Gravel	9.84E-04 - 9.84E-02 3.00E-04 - 3.00E-02	9.84E-03 3.00E-03	0.24 - 0.38	0.31	0.40 - 0.52 (0.70) - (0.90)	0.46 (0.80)	-- - -- -- - --	2.09E+01 (1.40E+06)
Sand (coarse)	3.0E-06 - 2.0E-02 (9.0E-07) - (6.0E-03)	2.4E-04 (7.3E-05)	0.31 - 0.46	0.385	0.40 - 0.52 (0.70) - (0.90)	0.46 (0.80)	-- - -- -- - --	2.09E+01 (1.40E+06)
Sand (fine)	6.6E-07 - 6.6E-04 (2.0E-07) - (2.0E-04)	2.1E-05 (6.3E-06)	0.26 - 0.53	0.40	0.40 - 0.52 (0.70) - (0.90)	0.46 (0.80)	-- - -- -- - --	2.09E+01 (1.40E+06)
Silt	3.3E-09 - 6.6E-05 (1.0E-09) - (2.0E-05)	4.6E-07 (1.4E-07)	0.34 - 0.61	0.475	0.69 - 1.39 (1.20) - (2.40)	1.04 (1.80)	3.58E+01 - 4.92E+01 (2.40E+06) - (3.30E+06)	4.25E+01 (2.85E+06)
Clay	3.3E-11 - 1.5E-08 (1.0E-11) - (4.7E-09)	7.1E-10 (2.2E-10)	0.34 - 0.60	0.47	0.49 - 0.64 (0.85) - (1.10)	0.56 (0.98)	4.47E+01 - 5.37E+01 (3.00E+06) - (3.60E+06)	4.92E+01 (3.3E+06)
Rocks								
Limestone, Dolomite	3.3E-09 - 2.0E-05 (1.0E-09) - (6.0E-06)	2.5E-07 (7.7E-08)	0 - 0.20	0.10	0.87 - 1.91 (1.50) - (3.30)	1.39 (2.40)	3.17E+02 - 8.20E+01 (2.13E+06) - (5.50E+06)	1.99E+02 (1.34E+07)
Karst Limestone	3.3E-06 - 3.3E-02 (1.0E-06) - (1.0E-02)	3.3E-04 (1.0E-04)	0.05 - 0.50	0.275	1.44 - 2.48 (2.50) - (4.30)	1.96 (3.40)	3.17E+02 - 8.20E+01 (2.13E+06) - (5.50E+06)	1.99E+02 (1.34E+07)
Sandstone	9.8E-10 - 2.0E-05 (3.0E-10) - (6.0E-06)	1.4E-07 (4.2E-08)	0.05 - 0.30	0.18	1.33 - 3.76 (2.30) - (6.50)	2.54 (4.40)	3.17E+01 - 7.46E+01 (2.13E+06) - (5.00E+06)	5.31E+01 (3.56E+06)
Shale	3.3E-13 - 6.6E-09 (1.0E-13) - (2.0E-09)	4.6E-11 (1.4E-11)	0 - 0.10	0.0525	0.87 - 2.02 (1.50) - (3.50)	1.44 (2.50)	3.54E+01 - 8.20E+01 (2.38E+06) - (5.50E+06)	5.87E+01 (3.94E+06)
Fractured Igneous and Metamorphic	2.6E-08 - 9.8E-04 (8.0E-09) - (3.0E-04)	5.1E-06 (1.5E-06)	0 - 0.10	0.05	1.47 - 3.83 (2.50) - (6.60)	2.65 (4.58)	-- - -- -- - --	3.28E+01 (2.20E+06)
Unfractured Igneous and Metamorphic	9.8E-14 - 6.6E-10 (3.0E-13) - (2.0E-10)	8.0E-12 (2.4E-12)	0 - 0.05	0.025	1.47 - 3.83 (2.50) - (6.60)	2.65 (4.58)	-- - -- -- - --	3.28E+01 (2.20E+06)

Notes: Thermal conductivity values are taken to represent that of materials in the dry condition.

* hydraulic conductivity and porosity data from Domenico and Schwartz (1990).

** thermal property data from Hellstrom (1991). For sedimentary rocks, Hellstrom lists only c_s . In these cases, a density of 2500 kg/m³ is assumed.

The mineral content of the material is important because it dictates the overall thermal properties of the material. Mineral content, because it affects rock solubility, also has an important control over the quality of water found in the material as well as its porosity. The higher the solubility of minerals in the material, the higher the dissolved solids in the ground water and the higher the secondary porosity is likely to be. Examples of the most commonly occurring soluble minerals include carbonate, gypsum, and salts.

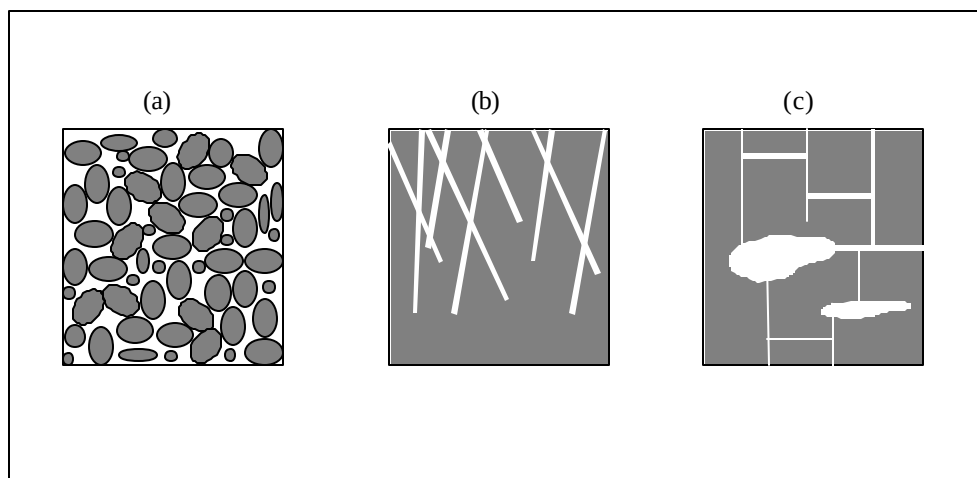


Figure 3.1: Types of openings in geologic materials **(a)** pore spaces, e.g. sedimentary deposits (primary porosity), **(b)** fractures, e.g. igneous, metamorphic, sedimentary rocks, and clayey soils (secondary porosity), and **(c)** solution cavities e.g. limestone and dolomite (secondary porosity).

The porosity is a very important property of the material. Rocks originate under higher heat and pressure environments than soils and consequently generally possess lower porosities. Lower porosities in rocks result in higher contact area between grains and therefore higher thermal conductivities but lower hydraulic conductivities than soils, regardless of mineral content. In saturated materials, increased porosity results in increased heat capacities and therefore lower thermal diffusivities. Porosity is also an important controlling influence on hydraulic conductivity (Freeze and Cherry, 1979). Materials with higher porosity generally also have higher hydraulic conductivity. However, this correlation does not hold for fine-grained soils (see Table 3.1.). Porosity and hydraulic conductivity of soils and rocks are increased by secondary porosity features as shown in Figure 3.1.

The degree of saturation has an obvious impact on the hydraulic and thermal properties of geologic materials. Unsaturated hydraulic conductivities are orders of magnitude less

than saturated hydraulic conductivities and water in the unsaturated zone is not capable of flow to a well. Materials with pore spaces filled with air also possess lower thermal conductivities than materials that are filled with water. The degree of saturation is also directly related to the water table elevation, which is dependent upon the ground-water recharge rate from rainfall. This is not a property of rock type, but of locality, and is discussed in the following subsection.

3.2 Ground-Water Regions Of North America

Given the general hydraulic and thermal properties of various soils and rock types, it is important to know where they occur in nature. The concept of “ground-water regions” is useful in summarizing the spatial variability of geologic and Hydrogeological conditions. In the context of SCWs, this allows a general comparison between regions of known operating installations to those that have not yet been explored.

The categorization of the United States into ground-water regions was first completed by Meinzer (1923). Several updates and revisions have been done as new developments were made. Heath (1984) produced a classification scheme, which is widely cited in the literature. Heath's scheme is based on the following items of ground-water systems:

- The components of the system and their arrangement,
- The nature of the water-bearing openings (porous or fractured),
- The mineral composition of the rock matrix,
- The hydraulic properties of the dominant aquifers, and
- The nature and location of recharge and discharge areas

As discussed in the previous subsection, the properties that impact fluid flow in geologic materials are also important to the heat transfer. Since Heath (1988) has extended the coverage of this classification scheme to include all of North America, it appears to be a useful means to generalize the hydrogeology of SCW installations.

Heath (1988) divided North America into 28 ground-water regions as shown in Figure 3.2. Table 3.2 provides a summary of each region with regard to Hydrogeological situation and lists some common ranges of hydraulic properties found in each region.

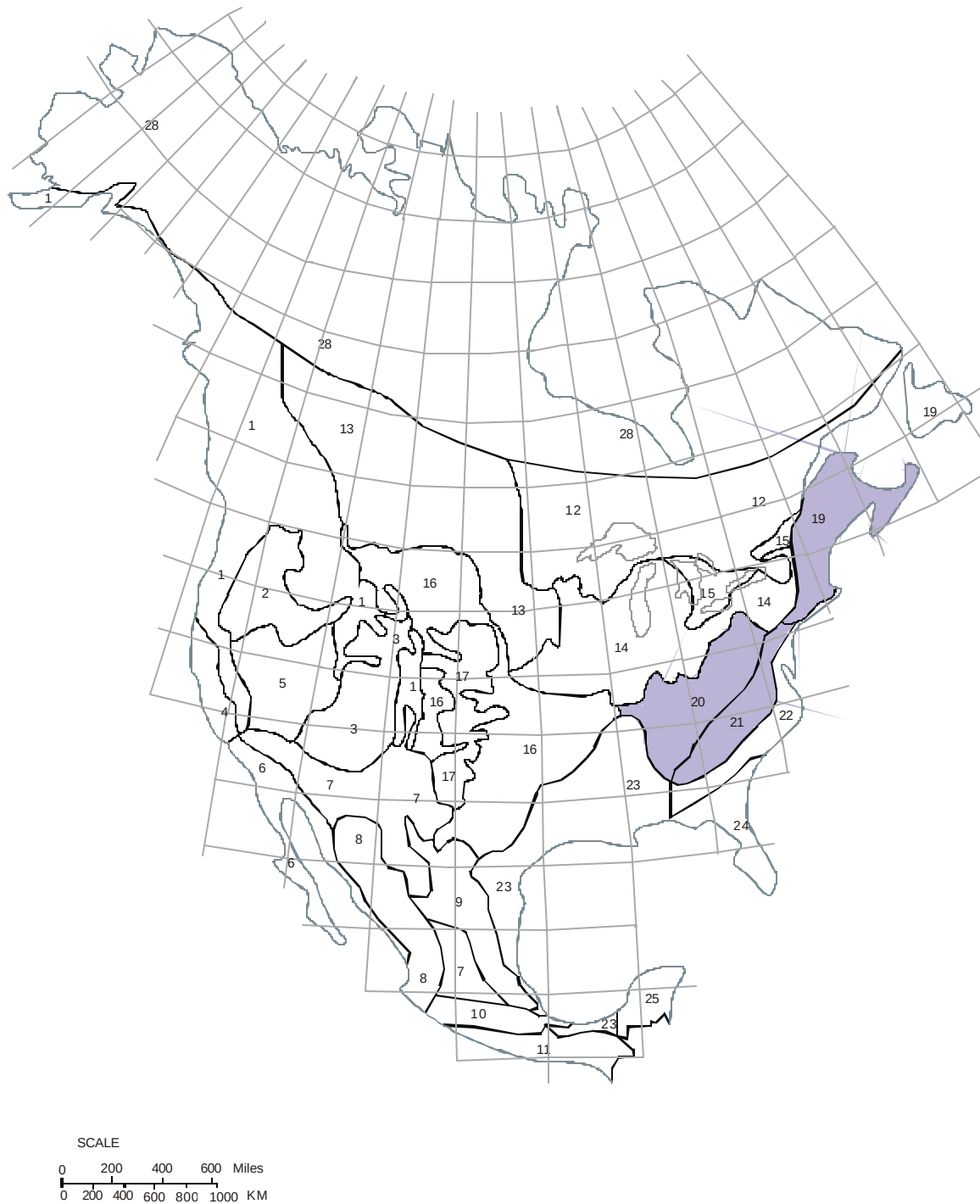


Figure 3.2: Ground-water regions of North America. Source: Heath (1988).
Regions with documented standing column wells are shown shaded.
Key to regions on following pages.

R&D Studies applied to SCW design

Geological and Hydrogeological Characteristics

Key to Figure 3.2, Ground-water regions of North America.

Region	Hydrogeologic Situation*	Common Ranges in Hydraulic Characteristics of the Dominant Aquifers							
		Transmissivity		Hydraulic Conductivity		Recharge Rate		Well Yield	
		(ft ² /day)	(m ² /day)	(ft/day)	(m/day)	(in/yr)	(mm/yr)	(gpm)	(m ³ /min)
1. Western Mountain Ranges	Mountains with thin soils over fractured rocks alternating with valleys underlain by alluvial and glacial deposits.	5 - 5,382	0.5 - 500	0.03 - 66	0.01 - 20	0.1 - 2	3 - 50	13 - 264	0.05 - 1
2. Columbia Lava Plateau	Low mountains and plains with thin soils over thick lava sequences interbedded with unconsolidated deposits.	21,528 - 5.38E+06	2,000 - 500,000	3.28 - 9,843	1 - 3,000	0.2 - 10	5 - 250	238 - 47,551	0.9 - 180
3. Colorado Plateau and Wyoming Basin	A region of canyons, cliffs, and plains of thin soils over fractured sedimentary rocks.	5 - 1,076	0.5 - 100	0.03 - 16	0.01 - 5	0.1 - 2	3 - 50	13 - 528	0.05 - 2
4. Central Valley and Pacific Coast Ranges	Relatively flat valleys of thick alluvial deposits bordered along the coast by low mountains composed of semiconsolidated sedimentary rocks and volcanic deposits.	108 - 107,639	10 - 10,000	98.43 - 1,969	30 - 600	0.4 - 4	10 - 100	132 - 5,283	0.5 - 20
5. Great Basin	Alternating flat basins of thick alluvial deposits and short, subparallel mountain ranges composed of crystalline and sedimentary rocks.	108 - 107,639	10 - 10,000	32.81 - 1,640	10 - 500	0.2 - 2	5 - 50	132 - 2,642	0.5 - 10
6. Coastal Alluvial Basins	Relatively flat valleys of thick alluvial deposits separated by mountain ranges composed of volcanic, metamorphic, and sedimentary rocks.	108 - 10,764	10 - 1,000	16.40 - 328	5 - 100	0.2 - 2	5 - 50	132 - 2,642	0.5 - 10
7. Central Alluvial Basins	Relatively flat valleys of thick alluvial deposits separated by discontinuous mountain ranges composed of volcanic, metamorphic, and sedimentary rocks.	108 - 21,528	10 - 2,000	32.81 - 656	10 - 200	0.2 - 2	5 - 50	132 - 2,642	0.5 - 10
8. Sierra Madre Occidental	Thin regolith over a complex sequence of volcanic rocks.	1,076 - 107,639	100 - 10,000	32.81 - 1,640	10 - 500	0.4 - 4	10 - 100	132 - 5,283	0.5 - 20
9. Sierra Madre Oriental	Mountain ranges and valleys underlain by a thin regolith over sedimentary rocks.	108 - 10,764	10 - 1,000	3.28 - 164	1 - 50	0.2 - 2	5 - 50	132 - 1,321	0.5 - 5
10. Faja Volcanica Trans-mexicana	Mountainous area underlain by thin regolith over a complex sequence of volcanic rocks.	1,076 - 107,639	100 - 10,000	32.81 - 1,640	10 - 500	0.4 - 4	10 - 100	132 - 5,283	0.5 - 20
11. Sierra Madre Del Sur	Mountainous area underlain by thin regolith over metamorphic, sedimentary, and volcanic rocks.	54 - 53,820	5 - 5,000	3.28 - 984	1 - 300	0.4 - 4	10 - 100	26 - 2,642	0.1 - 10

*An average thickness of about 5 m (16.4 ft) was used as the break point between thin and thick.

R&D Studies applied to SCW design

Geological and Hydrogeological Characteristics

Key to Figure 3.2 (continued), Ground-water regions of North America.

Region	Hydrogeologic Situation*	Common Ranges in Hydraulic Characteristics of the Dominant Aquifers							
		Transmissivity		Hydraulic Conductivity		Recharge Rate		Well Yield	
		(ft ² /day)	(m ² /day)	(ft/day)	(m/day)	(in/yr)	(mm/yr)	(gpm)	(m ³ /min)
12. Precambrian Shield	Hilly terrane underlain by glacial deposits over metamorphic rocks.	108 - 5,382	10 - 500	0.33 - 98	0.1 - 30	0.4 - 12	10 - 300	26 - 264	0.1 - 1
13. Western Glaciated Plains	Hilly plains underlain by glacial deposits over sedimentary rocks.	269 - 26,910	25 - 2,500	0.66 - 328	0.2 - 100	0.2 - 8	5 - 200	53 - 528	0.2 - 2
14. Central Glaciated Plains	Area of diverse topography, ranging from plains in Iowa to the Catskill Mountains in New York, underlain by glacial deposits over sedimentary rocks.	1,076 - 21,528	100 - 2,000	6.56 - 984	2 - 300	0.2 - 12	5 - 300	53 - 528	0.2 - 2
15. St. Lawrence Lowlands	Hilly area underlain by glacial deposits over sedimentary rocks.	1,076 - 21,528	100 - 2,000	6.56 - 984	2 - 300	0.2 - 12	5 - 300	53 - 528	0.2 - 2
16. Central Non-Glaciated Plains	Plains underlain by thin regolith over sedimentary rocks.	3,229 - 107,639	300 - 10,000	9.84 - 984	3 - 300	0.2 - 12	5 - 300	106 - 2,642	0.4 - 10
17. High Plains	Plains underlain by thick alluvial deposits over sedimentary rocks.	10,764 - 1.1E+05	1000 - 10,000	6.56 - 328	2 - 100	0.0 - 6	1 - 150	106 - 2,642	0.4 - 10
18. Alluvial Valleys	Thick deposits of sand and gravel, in places interbedded with silt and clay, underlying floodplains and terraces of streams.	2,153 - 538,196	200 - 50,000	98.43 - 6,562	30 - 2,000	2.0 - 20	50 - 500	106 - 5,283	0.4 - 20
19. Northeastern Appalachians	Hilly to mountainous area underlain by glacial deposits over fractured metamorphic and igneous rocks.	538 - 5,382	50 - 500	0.98 - 164	0.3 - 50	1.2 - 12	30 - 300	26 - 528	0.1 - 2
20. Appalachian Plateaus and Valley and Ridge	Hilly to mountainous area underlain by thin regolith over sedimentary rocks.	3,229 - 107,639	300 - 10,000	9.84 - 984	3 - 300	0.2 - 16	5 - 400	106 - 2,642	0.4 - 10
21. Piedmont and Blue Ridge	Hilly to mountainous area underlain by thick regolith over fractured metamorphic and igneous rocks.	108 - 2,153	10 - 200	0.33 - 7	0.1 - 2	1.2 - 12	30 - 300	26 - 264	0.1 - 1
22. Atlantic and Eastern Gulf Coastal Plain	Low-lying plain of thick interbedded sand, silt, and clay deposits overlying sedimentary rocks.	5,382 - 107,639	500 - 10,000	16.40 - 328	5 - 100	2.0 - 20	50 - 500	132 - 5,283	0.5 - 20
23. Gulf of Mexico Coastal Plain	Low-lying plain of thick interbedded sand, silt, and clay deposits.	5,382 - 107,639	500 - 10,000	16.40 - 328	5 - 100	2.0 - 20	50 - 500	132 - 5,283	0.5 - 20
24. Southeastern Coastal Plain	Low-lying area of thick layers of sand and clay over semiconsolidated carbonate rocks.	10,764 - 1.1E+06	1000 - 100,000	98.43 - 9,843	30 - 3,000	1.2 - 20	30 - 500	1,321 - 13,209	5 - 50

*An average thickness of about 5 m (16.4 ft) was used as the break point between thin and thick.

Key to Figure 3.2 (continued), Ground-water regions of North America.

Region	Hydrogeologic Situation*	Common Ranges in Hydraulic Characteristics of the Dominant Aquifers							
		Transmissivity		Hydraulic Conductivity		Recharge Rate		Well Yield	
		(ft ² /day)	(m ² /day)	(ft/day)	(m/day)	(in/yr)	(mm/yr)	(gpm)	(m ³ /min)
25. Yucatan Peninsula	Low-lying area of thin regolith over semiconsolidated carbonate rocks.	5,382 - 53,820	500 - 5,000	32.81 - 1,640	10 - 500	0.8 - 8	20 - 200	132 - 1,321	0.5 - 5
26. West Indies	Hilly and mountainous islands of igneous and volcanic rocks, overlain by thin regolith.	1,076 - 1.1E+05	100 - 10,000	9.84 - 984	3 - 300	0.2 - 12	5 - 300	26 - 2,642	0.1 - 10
27. Hawaiian Islands	Mountainous islands of complex volcanic rocks, overlain by thin regolith.	1.1E+05 - 1.1E+06	1.0E+04 - 1.0E+05	656.17 - 9,843	200 - 3,000	1.2 - 39	30 - 1000	106 - 5,283	0.4 - 20
28. Permafrost Region	Glacial deposits, perennially frozen, overlying fractured igneous, metamorphic, and sedimentary rocks.	108 - 21,528	10 - 2,000	32.81 - 656	10 - 200	0.2 - 4	5 - 100	3 - 528	0.01 - 2

*An average thickness of about 5 m (16.4 ft) was used as the break point between thin and thick.

3.3 Regions With Standing Column Well Installations

3.3.1 Northeastern Appalachians Region

The majority of currently known SCWs exist in the Northeastern Appalachians Region (Region 19, Figure 3.2). This region includes the states of Maine, Massachusetts, New Hampshire, New York, northwestern New Jersey, and also portions of southeastern Canada. Existing information implies that each of these is installed in igneous or metamorphic rock.

The Northeastern Appalachians Region is a hilly to mountainous region characterized by glacial deposits underlain by igneous and metamorphic rocks. The glacial deposits are typically 10 ft (3 m) to 30 ft (9 m) thick (Randall et al., 1988). The water table position commonly rises to within 6.5 ft (2 m) of the land surface each spring in the upland areas (Randall et al., 1988), but in parts of Atlantic Canada, where the bedrock is more permeable, the glacial deposits may remain unsaturated all year. According to the U.S. Geological Survey (1995), ground-water movement in this region is totally dependent on secondary openings (fractures) in the bedrock; inter-granular porosities are so small (0.7% to 2.8%), they can be considered insignificant. Fracture permeability in crystalline rocks is the result of cooling of igneous rocks, deformation of igneous and metamorphic rocks, faulting, jointing, and weathering. It is these crystalline rocks in which all the SCWs exist. A brief description of the aquifers and well characteristics found in them are summarized in Table 3.3.

Ground-water chemical quality is an important consideration for heat pumps and pumping equipment. Water in the crystalline rock aquifers is generally suitable for most uses because crystalline rocks generally are composed of virtually insoluble minerals. Further, ground water is in contact with a relatively small surface area in joints and fractures. Table 3.4 summarizes ground-water quality in crystalline aquifers of the Northeastern Appalachian Region. Locally, ground water may contain excessive concentrations of iron, manganese, sulfate, or radon (U.S. Geological Survey, 1995).

3.3.2 Appalachian Plateaus and Valley and Ridge Region

A number of SCWs have been identified in the Appalachian Plateaus and Valley and Ridge Region (Region 20, Figure 3.2). This region includes the states of Pennsylvania, West Virginia, eastern Kentucky, eastern Tennessee and the northeast of Alabama. This includes the SCW at Pennsylvania State University (described by Mikler, 1993) and one at Kutztown, PA. According to Mikler (1993), the test well at the Pennsylvania State University is installed in limestone. Existing information suggests that the Kutztown well is also installed in carbonate rock. Other installations found in the survey include several in Kentucky and one in Alabama.

Table 3.3
Crystalline Aquifers of the Northeastern Appalachian Region
Source: U.S. Geological Survey (1995)

State	Aquifer Description	Well Characteristics			
		Depth (feet)		Well Yield (gpm)	
		Common Range	Might Exceed	Common Range	Might Exceed
New York	Igneous and metamorphic rocks, generally confined	25 - 400	600	1 - 120	180
Connecticut	Gneiss and schist with some other metamorphic and igneous rock types. Generally unconfined in the upper 200 feet, might be confined at depth.	10 - 300	500	1 - 25	200
Maine	Igneous rocks include granite, gabbro, diorite, granodiorite, and pegmatite. Metamorphic rocks include schist, gneiss, quartzite, slate, and argillite. Locally confined at depth.	20 - 500	800	2 - 10	500
Massachusetts	Igneous and metamorphic rocks, predominantly gneiss and schist, confined.	100 - 400	1000	1 - 20	300
New Hampshire	Igneous and metamorphic rocks, generally confined.	100 - 600	800	1 - 10	100
Rhode Island	Indurated to metamorphosed sedimentary rocks in the vicinity of Narragansett Bay; igneous and metamorphic rocks, chiefly granite and gneiss, elsewhere.	100 - 300	500	1 - 20	50
Vermont	Igneous, metasedimentary, and metavolcanic rocks, generally confined.	100 - 600	800	1 - 10	100

The Appalachian Plateaus and Valley and Ridge Region is a hilly to mountainous region characterized by thin regolith underlain by sedimentary rocks. According to the U.S. Geological Survey (1997), the principal aquifers are the carbonate aquifers, primarily limestone, and sandstone aquifers. Ground-water flow is controlled by the presence of fractures in all aquifers as well as solution channels in carbonate aquifers. Limestone aquifers of the Waynesboro Formation in central Pennsylvania produce well yields reported to range from 25 to 210 gallons per minute. In contrast, well yields from sandstone in this area only range from 10 to 30 gallons per minute.

Ground-water quality in this region is reported to be suitable for municipal supplies and other purposes (U.S. Geological Survey, 1997). Due to the solubility of carbonate rocks, these aquifers generally contain very hard water (280 milligrams per liter) with total dissolved solids averaging about 330 milligrams per liter. The pH of the ground water is slightly basic, about 7.4 and iron concentrations are low, about 0.1 milligrams per liter, but concentrations as high as 8 milligrams per liter have been reported. Ground water in the fractured sandstone aquifers is moderately hard (100 milligrams per liter) with

relatively low total dissolved solids, averaging about 150 milligrams per liter. The pH of the ground water is slightly basic, about 7.4 and iron concentrations are low, about 0.1 milligrams per liter, but concentrations as high as 14 milligrams per liter have been reported.

Table 3.4

Ground-Water Quality in Crystalline Aquifers of the Northeastern Appalachian Region Source: U.S. Geological Survey (1995)

Property or Constituent	Range	Median	Number of Analyses
pH (standard units)	5.7 - 8.2	7.7	43
Hardness as CaCO ₃	14 - 186	68	42
Calcium (Ca)	4 - 66	23	36
Magnesium (Mg)	0.9 - 15	2.8	36
Sodium (Na)	2.7 - 40	8.4	37
Potassium (K)	0 - 5.3	2.6	36
Bicarbonate (HCO ₃)	4 - 205	62	41
Sulfate (SO ₄)	4.1 - 46	15	36
Chloride (Cl)	0.4 - 140	6.5	41
Fluoride (F)	0 - 0.6	0.1	37
Silica (SiO ₂)	8.1 - 28	18	37
Dissolved Solids	31 - 286	116	37
Nitrate (NO ₃)	0 - 16	0.2	59
Iron (Fe)	0.04 - 5.2	0.17	61
Manganese (Mn)	0 - 0.58	0.03	56

Note: All concentrations in milligrams per liter

3.3.3 Piedmont and Blue Ridge Region

A number of SCWs have been identified in the Piedmont and Blue Ridge Region (Region 21, Figure 3.2, Table 3.2). This region includes southern New Jersey, western Virginia, western North Carolina, western South Carolina and northern Georgia. Several wells are known in New Jersey and some indicated (but not verified) in North Carolina. No wells were found in the survey in the other states mentioned above.

The Piedmont and Blue Ridge Region is a hilly to mountainous region characterized by thick regolith (weathered rock) underlain by igneous and metamorphic rocks. It is geologically similar to the Northeastern Appalachian Region, except that it has not been glaciated. The regolith ranges in thickness from a feather to 131 ft (40 m) and the water table generally occurs near land surface in valleys and at depths of 26 ft (8 m) to 66 ft (20 m) in hilly areas (LeGrand, 1988). Sustained well yields range from about 5 to 105 gallons per minute (LeGrand, 1988).

R&D Studies applied to SCW design

Geological and Hydrogeological Characteristics

Ground-water quality in the crystalline rocks of this region is reported to be suitable for drinking and other uses (U.S. Geological Survey, 1997). The water is soft, with hardness levels of about 63 milligrams per liter. Total dissolved solids average about 120 milligrams per liter. The pH of the ground water is slightly acidic, about 6.7 and iron concentrations are low, about 0.1 milligrams per liter, but concentrations as high as 25 milligrams per liter have been reported.

4.0 The Standing Column Well Numerical Model

The objective of the numerical model is to predict the transient operation of the standing column well heat exchanger under varying load and flow conditions. The primary output of interest in this study is the exiting fluid temperature. In order to examine different standing column well designs and operating conditions the model must allow manipulation of the following parameters:

- Well diameter and depth
- Rock thermal and hydraulic properties
- Dip and suction tube size and position
- System flow and bleed rate
- Building/heat pump loads
- Rock temperature and thermal gradient
- Dip tube insulation
- Casing depth

The heat transfer processes affecting the standing column well performance need to be considered on two physical scales. Inside the borehole – within a relatively small radius – the heat transfer between the tubes, the surrounding fluid and the rock wall have to be considered. As the groundwater flow surrounding the borehole has a significant effect on its operation, the model must be extended beyond the borehole by two orders of magnitude in the radial direction. In addition the fluid flow inside and outside of the borehole is rather different. Inside the borehole the flow can be likened to turbulent pipe flow, in the rock fluid is flowing through a porous medium. Accordingly, as there is a need to model rather different physical scales and fluid flow regimes inside and outside the borehole, the model used here consists of a model of the borehole and a model of the surrounding rock that are coupled together. This requires iterative solution of each model in sequence. The relationship between the different domains of each model is shown in Figure 4.1.

Ground-water 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, are not considered in the present study. Consequently it can be assumed that the ground water flow and heat transfer is symmetrical about the centerline of the borehole. To model the groundwater flow and heat transfer surrounding the borehole a finite volume model that uses a mesh in two dimensions (axial and radial) has been developed. The borehole is modeled as a nodal network that is discretized over the length of the borehole. Fluid flow in the nodal model of the borehole is modeled using control volumes that coincide with those of the adjacent finite volume mesh. Each model is described in further detail below.

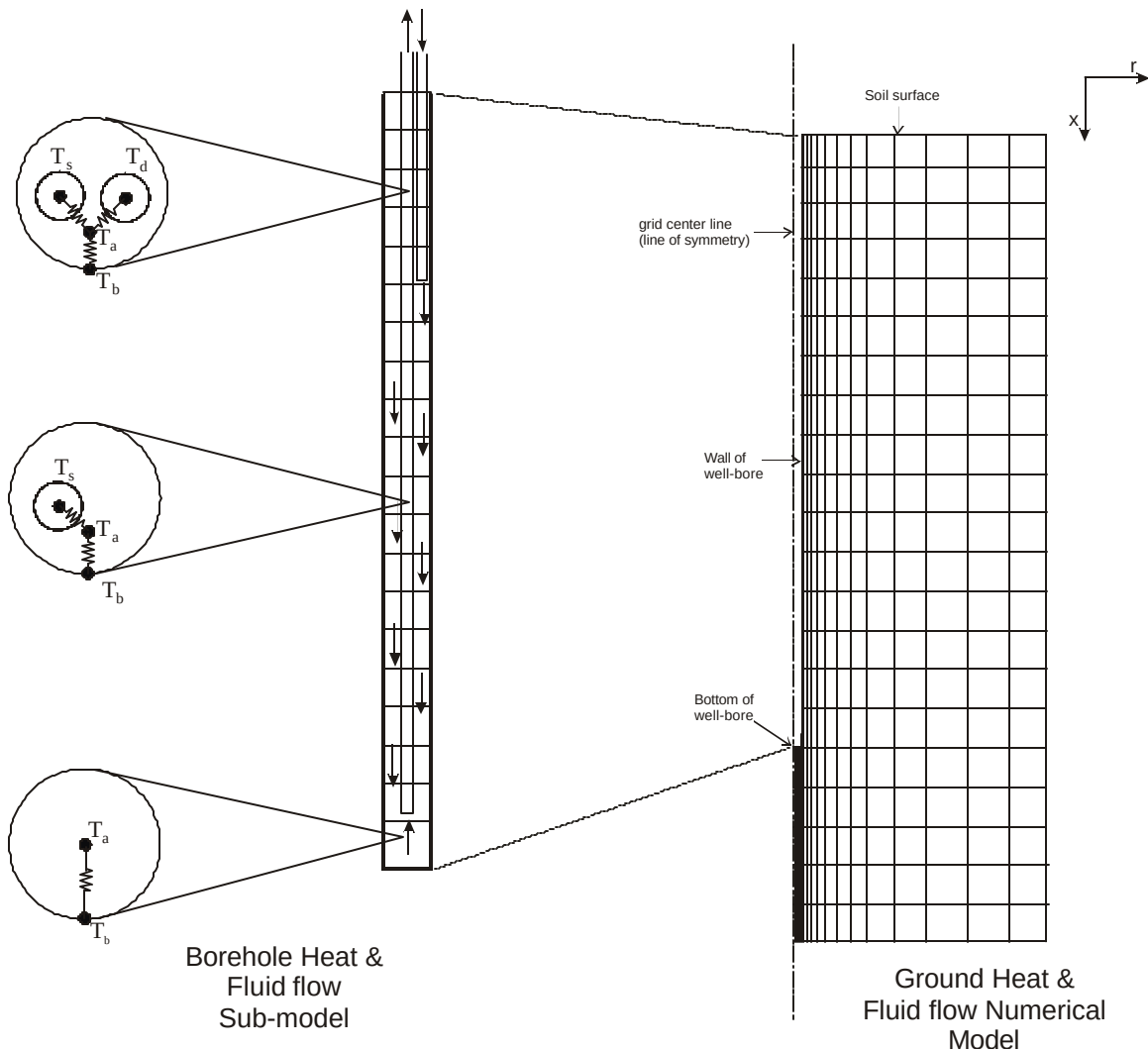


Figure 4.1: A diagram showing the relationship between the borehole and groundwater flow models.

4.1 Heat Transfer in Standing Column Wells

Conventional closed-loop heat exchangers in geothermal heat pump applications are often modeled assuming no ground-water 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 ground-water 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 4.2.

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 and casing. As the borehole wall is porous (where there is no casing) fluid is able to flow from the borehole wall into and out of the rocks porous matrix. The size 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 ground-water 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 (somewhere near half way down) there will be a balance point (no net pressure gradient) at which there will be no flow either into or out of the rock. This type of flow is illustrated in Figure 4.2 and 4.3.

The advection heat transfer due to the ground-water 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 ground-water 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.

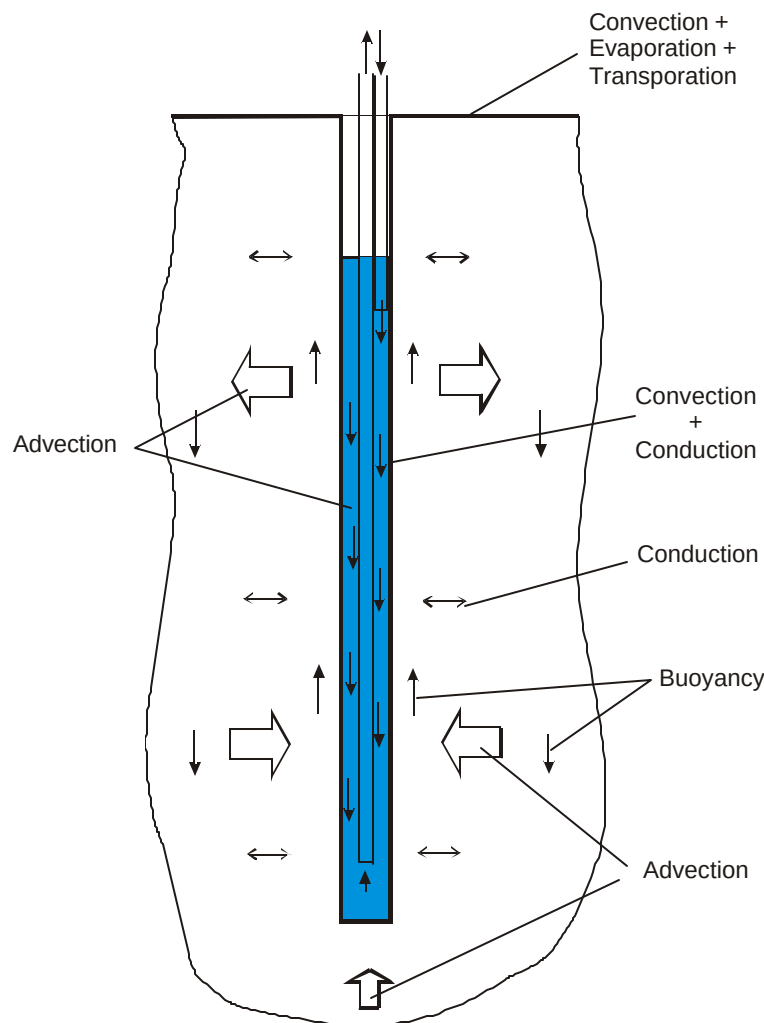


Figure 4.2: A diagram showing the different modes of heat transfer in and around a standing column well.

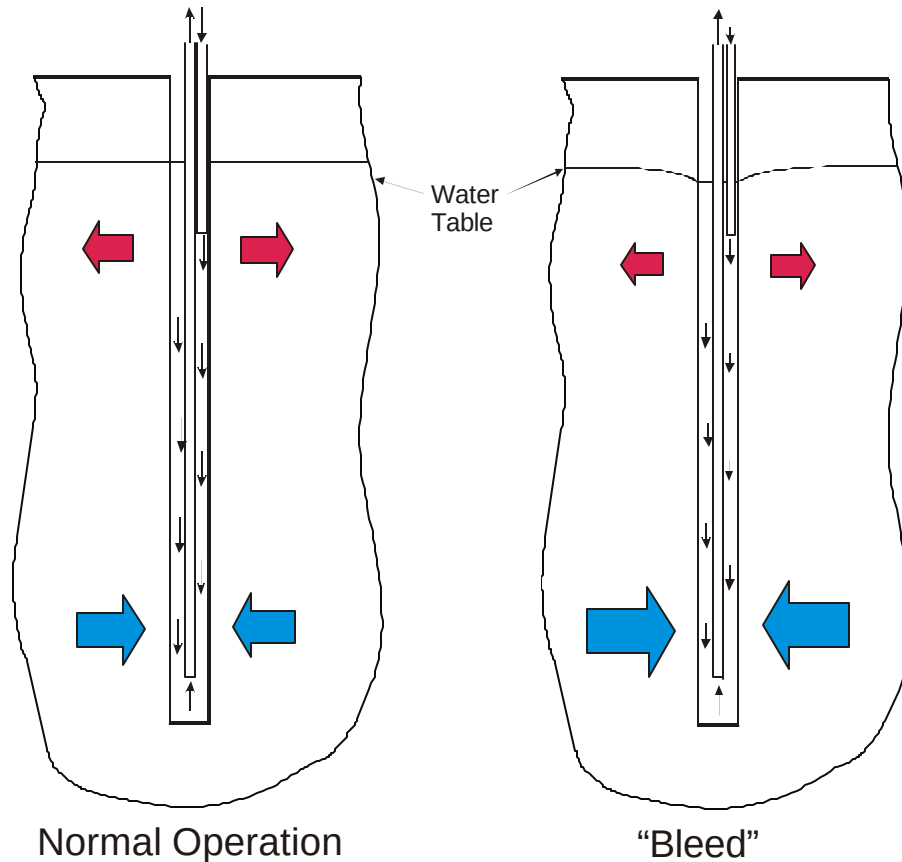


Figure 4.3: Advective heat transfer due to groundwater flow under normal operating conditions and 'bleed' conditions.

4.2 The Numerical Method

4.2.1 The calculation procedure

The mathematical model of standing column well systems has been reported in previous progress reports. In summary, the model consists of two components: (1) a well-bore sub model and (2) a finite-volume numerical model of flow and transport in the rock. For the borehole model and finite volume model to be coupled, the heat fluxes calculated by the borehole model must be used to set boundary conditions at the borehole wall in the finite volume model. In turn, the finite volume model calculates the ground flow and temperature fields and is able to pass the borehole wall temperatures back to the borehole model. Hence borehole wall temperatures are inputs to the borehole model and fluxes are output, and visa versa for the finite volume model.

For the heat fluxes to be consistent with the wall temperatures requires some iteration between the two models. It is also generally necessary to under-relax the temperatures passed to the borehole model. This necessity means that the model requires considerable

computer resources to calculate the transient performance of the well through a whole year.

In order to predict the response to time varying building/heatpump loads the temperature difference between the suction and discharge temperatures has to be set consistent with the predetermined annual building loads. This requires further iteration and under-relaxation between the two models. The sequence of the calculation and the transfer of information between the borehole model and the finite volume model is shown in Figure 4.4.

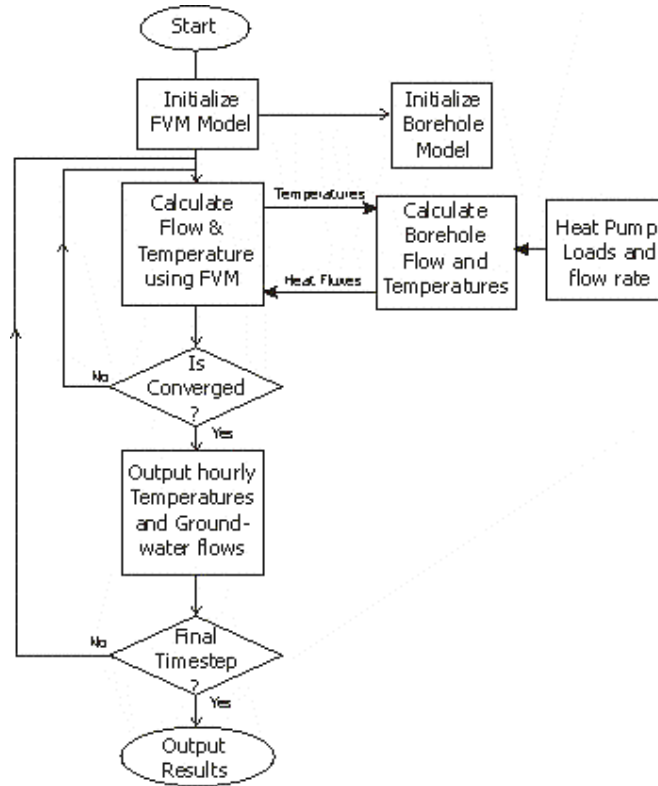


Figure 4.4: A flowchart showing the flow of information between the finite volume model and the borehole model and the progression of the calculation. Building loads and flow rate can be read in at each time step.

4.2.2 The Finite Volume Model

The finite volume method (FVM), as it is implemented in the solver used in this work, is described in this section by reference to a generic advection-diffusion equation. The FVM (Patankar 1980) starts from the integral form of the partial differential equation:

$$\frac{\partial}{\partial t} \int_V f dV + \int_S r \mathbf{f} \mathbf{v} \cdot \mathbf{n} dS = \int_S \Gamma \nabla f \cdot \mathbf{n} dS + \int_V Q dV \quad (4.1)$$

where f is the dependent variable (head or temperature in this context) and Γ is the diffusivity, V is the volume and S is the surface of a control volume and $\mathbf{n}$ is a vector normal to the surface. The left-hand term of the equation is the temporal term, the second term represents the Advective fluxes, the third term represents the diffusion fluxes and the fourth term represents sources and sinks. This generic form of advection-diffusion equation can be used to represent both the heat transfer and ground-water flow equations used in this work. Particular application to each of these processes is discussed in later sections.

A physical space approach for dealing with complex geometries can be derived from the vector form of the equation above. We will consider the advection fluxes, diffusion fluxes and temporal term in turn for one cell of the mesh. The approach taken here is discussed in Ferziger and Peric (1996).

4.2.1.1 Advection Fluxes

The advection flux term in discrete form is the sum of the advection fluxes through each cell face:

$$\int_S r f \mathbf{v} \cdot \mathbf{n} dS \approx \sum_i F_i^C \quad (4.2)$$

where $i = n, s, w, e$ for a 2D cell. If we consider the advection flux on a particular face of our prototype cell (say the east face) then

$$F_e^C = (r f \mathbf{v} \cdot \mathbf{n})_e S_e \quad (4.3)$$

where S_e is the surface area of the east face. This assumes that the value of the variable at the face can be approximated by the value at the centroid (midpoint) of the face. It is convenient, in terms of storage, to multiply the surface area by the normal vector and store an 'area vector'. For the east face of a two-dimensional cell this can be calculated in terms of the cell vertex coordinates:

$$\mathbf{n}_e S_e \equiv (y_{ne} - y_{se})\mathbf{i} + (x_{ne} - x_{se})\mathbf{j} \quad (4.4)$$

The subscripts ne and se refer to the north-east and south-east vertices of the cell (see diagram below). With these definitions the advection flux at the east face becomes:

$$F_e^C = r_e f_e (S^x v^x + S^y v^y)_e \quad (4.5)$$

From this it can be seen that each component of the velocity vector makes a contribution to the advection flux passing through the cell face. In the case of an orthogonal grid $S^x \equiv S_e$ and the second term in the brackets of eq.(5) would be zero. It is also necessary to interpolate the values of the variable f , and the velocity v , to values at the cell face.

$$F_e^D = \Gamma_e S_e \left(\frac{\partial f}{\partial x} \right)_{e'} + \Gamma_e S_e \left[\left(\frac{\partial f}{\partial n} \right)_e - \left(\frac{\partial f}{\partial x} \right)_{e'} \right]^{old} \quad (4.7)$$

where we use central differencing to get the gradients:

$$\left(\frac{\partial f}{\partial x} \right)_{e'} = \frac{(f_E - f_P)}{L_{P,E}} \quad \text{and} \quad \left(\frac{\partial f}{\partial n} \right)_e = \frac{(f_{E'} - f_{P'})}{L_{P',E'}} \quad (4.8)$$

The terms in the square brackets on the right of equation (4.7) are calculated explicitly, i.e. using the previous values of the variable. As the solution approaches convergence the terms $(\partial f / \partial x)_{e'}$ and $(\partial f / \partial x)_{e'}^{old}$ cancel out.

To proceed with this technique we need to be able to calculate the value of the independent variable at points P' and E', i.e. $f_{P'}$ and $f_{E'}$. This requires some interpolation from the centroid values. A convenient and generalized way to do this is to use the following interpolation formulae:

$$\begin{aligned} f_{P'} &= f_P + \nabla f_P \cdot (\mathbf{r}_{P'} - \mathbf{r}_P) \\ f_{E'} &= f_E + \nabla f_E \cdot (\mathbf{r}_{E'} - \mathbf{r}_E) \end{aligned} \quad (4.9)$$

and to use this we need to know ∇f . Now ∇f can be expressed in terms of the derivatives of the Cartesian coordinates giving the vector (for two-dimensions):

$$\nabla f = \frac{\partial f}{\partial x} \mathbf{i} + \frac{\partial f}{\partial y} \mathbf{j} \quad (4.10)$$

A simple way of evaluating this vector is provided by the Gauss' theorem; we approximate the derivative at the control volume centroid by the average value over the cell:

$$\left(\frac{\partial f}{\partial x_i} \right)_P \approx \frac{\int_V \frac{\partial f}{\partial x_i} dV}{\Delta V} \quad (4.11)$$

If we consider the derivative $\partial f / \partial x_i$ as the divergence of the vector $f \mathbf{i}$ the volume integral of equation (4.8) can be transformed into a surface integral:

$$\int_V \frac{\partial f}{\partial x_i} dV = \int_S f \mathbf{i}_i \cdot \mathbf{n} dS \approx \sum_m f_m S_m^i, \quad m = n, s, w, e, \dots \quad (4.12)$$

This allows the calculation of the gradient of f with respect to x at the control volume centroid by summing the products of the variable at the face with the x -components of the surface vectors and dividing by the cell volume:

$$\left(\frac{\partial f}{\partial x_i} \right)_P \approx \frac{\sum_m f_m S_m^i}{\Delta V} \quad (4.13)$$

The other piece of information we need to make the interpolation is the position vectors $\mathbf{r}_{P'}$ and $\mathbf{r}_{E'}$. Given that we know the position of the cell centroid and the centroid of each face we can use some vector subtraction:

$$\begin{aligned} \mathbf{r}_{P'} &= \mathbf{r}_e - [(\mathbf{r}_e - \mathbf{r}_P) \cdot \mathbf{n}] \mathbf{n} \\ \mathbf{r}_{E'} &= \mathbf{r}_e - [(\mathbf{r}_e - \mathbf{r}_E) \cdot \mathbf{n}] \mathbf{n} \end{aligned} \quad (4.14)$$

Finally we can write our discrete equation as

$$F_e^D = \Gamma_e S_e \frac{(f_E - f_P)}{L_{P,E}} + \Gamma_e S_e \left[\frac{(f_{E'} - f_{P'})}{L_{P',E'}} - \frac{(f_E - f_P)}{L_{P,E}} \right]^{old} \quad (4.15)$$

This can be simplified further by using only the length $L_{P',E'}$ only so that

$$F_e^D = \Gamma_e S_e \frac{(f_E - f_P)}{L_{P',E'}} + \frac{\Gamma_e S_e}{L_{P',E'}} [(f_{E'} - f_{P'}) - (f_E - f_P)]^{old} \quad (4.16)$$

Doing this allows us to store the quantity $\Gamma_e S_e / L_{P',E'}$ as a diffusion conductance for each face only. By substituting our interpolation formulae into equation (4.16) we arrive at:

$$F_e^D = \frac{\Gamma_e S_e}{L_{P',E'}} (f_E - f_P) + \frac{\Gamma_e S_e}{L_{P',E'}} [\nabla f_E \cdot (\mathbf{r}_E - \mathbf{r}_E) - \nabla f_P \cdot (\mathbf{r}_P - \mathbf{r}_P)]^{old} \quad (4.17)$$

Where the right hand terms are calculated as a deferred correction. If the grid is orthogonal, then it can be seen that the deferred correction becomes zero and the discrete equation becomes equivalent to that for orthogonal grids.

4.2.1.3 Temporal Discretization

We can think of time as a one-way coordinate, in that the past state influences the future but never the other way around. Hence we step forward in time from some initial condition when solving our transient conduction problem. In formulating a finite volume solution we need to integrate the partial differential equation. In a transient problem we need to integrate with respect to time also. Hence we integrate from the current time t^n using a fixed time step Δt to a new time t^{n+1} so that,

$$\int_V \int_{t^n}^{t^{n+1}} \frac{\partial r f}{\partial t} dt dV = \int_{t^n}^{t^{n+1}} \int_V \frac{\partial}{\partial x} \left(\Gamma \frac{\partial f}{\partial x} \right) dV dt \quad (4.16)$$

If we assume that the grid point value of the dependent variable prevails for the whole control volume then we can write,

$$\int_V \int_{t^n}^{t^{n+1}} \frac{\partial f}{\partial t} dt dV \approx \frac{\Delta V}{\Delta t} (f_P^{n+1} - f_P^n) \quad (4.17)$$

where DV is the volume of the cell. We also need to deal with the integration in time of the right-hand side of our equation. If we leave the diffusion fluxes in terms of F^D for the four faces of our two-dimensional control volume (n, s, w, e) we arrive at,

$$r \frac{\Delta V}{\Delta t} (f_P^{n+1} - f_P^n) = \int_{t^n}^{t^{n+1}} [F_n^D + F_s^D + F_w^D + F_e^D] dt \quad (4.18)$$

We must now make some assumption about how the diffusion fluxes vary from one time step to the next. We can make a general approximation which is the weighting of the old and new values so that,

$$r \Delta V (f_P^{n+1} - f_P^n) = f [F_n^D + F_s^D + F_w^D + F_e^D]^{n+1} \Delta t + (1-f) [F_n^D + F_s^D + F_w^D + F_e^D]^n \Delta t \quad (4.19)$$

If $f=0$ then the new value of f_P (at time level $n+1$) is entirely in terms of values at the previous time step. The equation for each node could then be solved directly and independently of the equations for the other nodes. This type of scheme is called *explicit* and has obvious computational advantages. However, this scheme has a numerical stability limitation. If f is anything other than zero the scheme is *implicit*. This means that the equations for each node have to be solved simultaneously. If f is 1 the scheme is said to be *fully implicit*. The fully implicit approach results in the following discretized equation,

$$r \Delta V (f_P^{n+1} - f_P^n) = [F_n^D + F_s^D + F_w^D + F_e^D]^{n+1} \Delta t \quad (4.20)$$

It can be seen that the temporal term is equivalent to first-order backwards differencing in time. The discretized equation can then be said to be first-order accurate in time and second-order accurate in space. This scheme is unconditionally stable. It is this fully implicit formulation that has been used in this project.

In order to make calculations of SCW performance over a whole year (8760 hours) it was necessary to make a compromise between computational speed and detail representation of the time varying boundary conditions. The building/heat pump load data was available on an hourly basis. However it was not feasible to use hourly time steps due to the excessive computation time. The load data was consequently integrated so that six hour time steps could be used.

4.1.2.4 Solution of the Equations

After integrating the p.d.e and applying the discretization procedures we have discussed so far we arrive at an algebraic equation for each control volume of the form,

$$a_p f_p = \sum a_{nb} f_{nb} + b \quad (4.21)$$

where, a_p for one control volume becomes one of a_{nb} for the next cell. In other words, for the whole discretized domain we have a set of algebraic equations that are coupled via neighboring cells. We can assemble these equations into matrices so that the algebraic problem we have to solve can be expressed as,

$$[\mathbf{A}][\mathbf{f}] = [\mathbf{Q}] \quad (4.22)$$

where $[\mathbf{A}]$ is a square matrix of coefficients and $[\mathbf{f}]$ and $[\mathbf{Q}]$ are vectors. This set of algebraic equations is a linearized Discretization of the p.d.e. In order to deal with the non-linearities of the equation (due to advection for example) it is necessary to iteratively re-linearize the equations and apply a linear equation solver at each iteration. There are many equation solvers available but the algorithm known as the Semi-Implicit Method (SIP) or Stones Algorithm (Stone 1968) has been used, along with the BiCGSTAB algorithm (van der Vorst 1981).

The finite volume model has previously been validated against analytical solutions to a number of diffusion and advection-diffusion problems. It was specifically tested against solutions for cylindrical conduction heat transfer for this work. The borehole model was tested using the data recorded by Mikler (1993).

4.2.3 Application to Ground-water flow and Heat Transfer

In order to model heat transfer and ground-water flow around the standing column well it is necessary to solve two sets of partial differential equations. A typical numerical mesh over which these equations are solved is shown in Figure 4.6. In this work saturated flow has been assumed and so Darcy's equation is used to model saturated ground-water flow. Preliminary calculations of the well draw-down show it to be less than one meter. Hence this effect is negligible compared with the overall 320m (1000ft) of the borehole and has been ignored. The equation of flow is written in terms of head, and is given by:

$$\nabla \cdot (K \nabla h) = S_s \frac{\partial h}{\partial t} \quad (4.23)$$

where:	K	= hydraulic conductivity	(m/s [ft/h])
	h	= hydraulic head	(m [ft])
	S_s	= specific storage	(-)
	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 ground-water 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:

$$k_{eff} = nk_l + (1-n)k_s \quad (4.24)$$

where,

- n is the porosity;
- k_l is thermal conductivity of fluid (W/m.K [Btu/hr.ft.°F]);
- k_s is thermal conductivity of solid (W/m.K [Btu/hr.ft.°F]).

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

$$[nr_l C_{pl} + (1-n)r_s C_{ps}] \frac{\partial T}{\partial t} + r_l C_{pl} V_i \nabla T - \nabla \cdot (k_{eff} \nabla T) = Q \quad (4.25)$$

where,

- V_i is average linear groundwater velocity vector (m/s [ft/min]);
- n is the porosity (-);
- k_{eff} is effective thermal conductivity (W/m.K [Btu/hr.ft.°F]);
- r is density (kg/m³ [lbm/ft³]);
- C_p is specific heat (J/kg.K [Btu/lbm.°F]);
- Q is source/sink (W/m³ [Btu/hr.ft³]).

Subscripts: l = water;
 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 (4.25) and the equation for head (4.24) are coupled by the fluid velocity. The fluid velocity is obtained from the darcian ground-water flux as follows:

$$v = -\frac{K}{n} \nabla h \quad (4.26)$$

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. It can be seen that both the energy equation and the equation for ground-water head are forms of advection-diffusion equation (4.1). Accordingly they can both be treated by the solution technique described in the previous section by suitable choice of constant coefficients.

Boundary conditions for the SCW heat transfer numerical model are specified as zero flux at the centerline (symmetry) and top surface. The outer boundary (at the right in Fig. 4.6) and the lower boundary have the temperature set according to depth with a constant temperature gradient applied. Boundary conditions for the ground-water flow problem are specified as constant head on the domain boundaries. For the purposes of calculating

the ground heat transfer the part of the mesh corresponding to the borehole is made adiabatic (i.e. the finite volume numerical model does not calculate temperatures within the borehole). Special boundary conditions are applied at the borehole wall to achieve coupling between the borehole thermal model and the finite volume model.

Figure 4.6 also shows the form of the numerical grid used in the finite volume model calculations. The grid is in the radial-axial plane. After conducting some grid independence calculations a final grid size of 160x70 was chosen as the best compromise between accuracy and computational speed.

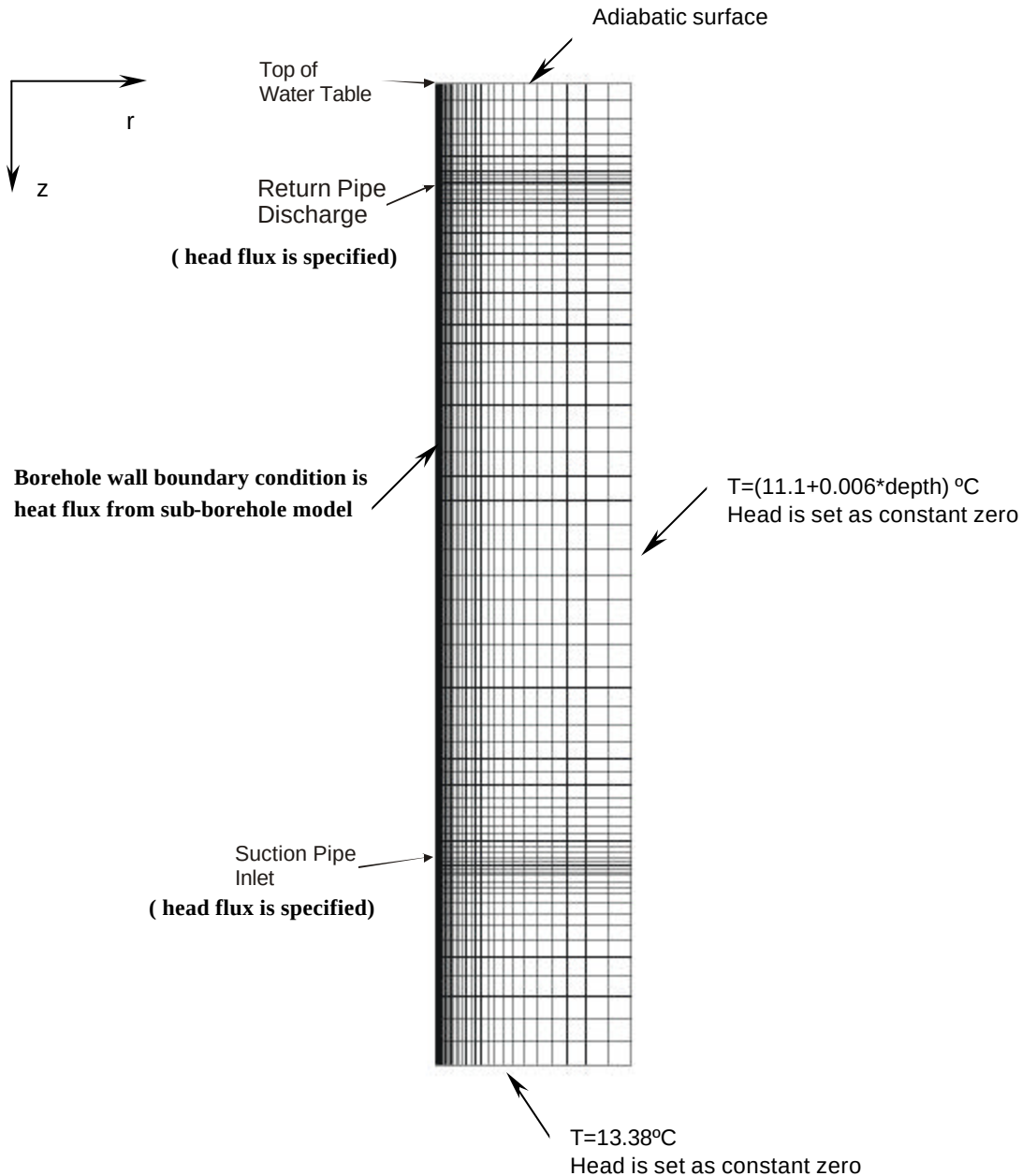


Figure 4.6: A typical numerical mesh for modeling standing column well ground-water flow and heat transfer.

The zone of the mesh corresponding to the borehole is treated rather differently when solving for the ground-water flow. In this case the fluid flow has to be calculated within the borehole by the numerical model by using solving the ground-water flow equation (4.23). This is necessary to find the flow through the wall of the borehole driven by the pressure distribution within and adjacent the borehole. Boundary conditions of constant flux are specified at the positions corresponding to the end of the discharge and suction pipes. These boundary conditions have to be consistent with the flow boundary conditions used in the borehole thermal model. To calculate the flow inside the borehole using equation (4.23) the proportionality constant (hydraulic conductivity) has to be re-defined so that the Darcy flux equation retains the same form ($q = KDh/Dx$) – a linear relationship between the flux and the hydraulic gradient.

The head loss (Dh) in a pipe is given by the Darcy-Weisbach formula:

$$\Delta h = f \frac{l}{d} \frac{u^2}{2g} \quad (4.27)$$

where, d = the pipe diameter (m [ft])
 f = the friction factor (-)
 u = mean fluid velocity (m/s [ft/h])

For laminar flow, $f = 64/Re$ and re-arranging terms to keep the Darcy form gives the following definition of the proportionality constant:

$$K_{laminar} = \frac{d^2 r_0 g}{32m(T)} \quad (4.28)$$

This proportionality constant is also given by Bear (1972), and this type of laminar flow is known as Hagen-Poiseuille flow. This is used to set the hydraulic conductivity within the borehole for the finite volume model.

4.3 The Borehole Model

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 4.7. The thermal network at a particular vertical position varies depending on the presence of the suction and discharge pipes.

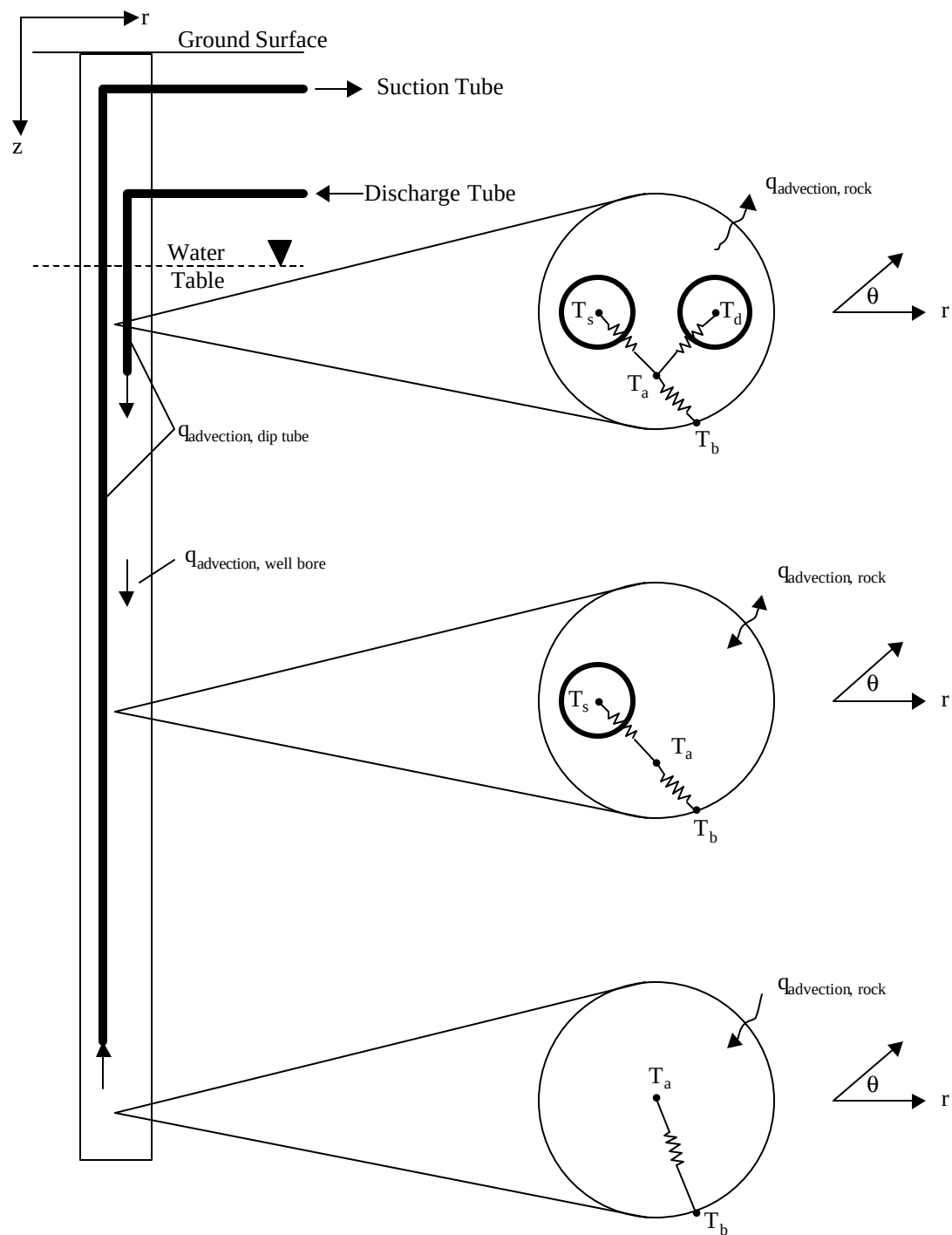


Figure 4.7. The well bore thermal model.

4.3.1 The Borehole Numerical Model

An energy balance can be formulated at each z plane in the well bore corresponding to the z plane in the F.V. model of the porous medium:

$$\frac{dT_{a,z}}{dt} V r c_p = q_{convection,suction\ tube} + q_{convection,discharge\ tube} + q_{convection,rock} + q_{advection,rock} + q_{advection,annulus} \quad (4.29)$$

where,

- $T_{a,z}$ = the fluid temperature in the annular region ($^{\circ}\text{C}$ [$^{\circ}\text{F}$])
- V = the volume of water in the annular region (m^3 [ft^3])
- r = the density of water in the annular region (kg/m^3 [lbm/ft^3])
- c_p = specific heat of water ($\text{J}/\text{kg}\cdot\text{K}$ [$\text{Btu}/\text{lbm}\cdot^{\circ}\text{F}$]).

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

$$q_{convection,m} = \frac{1}{R_m} (T_m - T_{a,z}) \quad (4.30)$$

where,

- R = the thermal resistance ($^{\circ}\text{C}/\text{W}$ [$^{\circ}\text{F}/\text{ft}$])
- m refers to each of the suction tube, the discharge tube, and the rock.

The thermal resistance is defined generally as:

$$R_m = \frac{1}{A_{i,m}} \left[\frac{1}{h_{i,m}} + \frac{r_i}{k_{pipe}} \ln \left(\frac{r_i}{r_o} \right) + \frac{r_i}{r_o} \left(\frac{1}{h_o} \right) \right] \quad (4.31)$$

where,

- A = area (m^2 [ft^2])
- r = radius (m [ft])
- k = thermal conductivity ($\text{W}/\text{m}\cdot\text{K}$ [$\text{Btu}/\text{hr}\cdot\text{ft}\cdot^{\circ}\text{F}$])
- i = inner surface
- o = outer surface
- h = the convection coefficient ($\text{W}/\text{m}\cdot\text{K}$ [$\text{Btu}/\text{hr}\cdot\text{ft}\cdot^{\circ}\text{F}$])
- = $\frac{Nu\ k_{fluid}}{D_h}$
- D_h = hydraulic diameter (m [ft])

Determination of the Nusselt number (Nu) for forced convection at each surface is discussed in the following section. The flow rates will be determined from the solution of the flow problem. The 2nd and 3rd terms of equation 4.31 do not apply to convection heat transfer at the borehole wall. The advection heat transfer rates in equation (4.29) are defined as:

$$q_{advection,n} = \dot{m} c_p (T_n - T_{a,z}) \quad (4.32)$$

where, $\dot{m}$ = the mass flow rate of the water (kg/s [lbm/h])
 n refers to each of the rock and the annular fluid at nodes $z-1$ and $z+1$.

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

$$\frac{dT_{tube,z}}{dt} V r c_p = q_{convection,annularregion} + q_{advection,tube} \quad (4.33)$$

where all terms are expressed as described above.

Now, equation (4.29) can be expressed in discrete form and $T_{a,z}$ can be isolated and likewise, equation (4.33) can be expressed in discrete form for each tube and $T_{discharge\ tube,z}$ and $T_{suction\ tube,z}$ can be isolated. The result is 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 will be calculated and passed to the finite volume model and used to set the flux boundary condition, the finite volume model in turn will be used to calculate new temperatures at the borehole wall. This procedure will be repeated until the borehole wall temperatures and fluxes at each z -level are consistent. The coupling of the two models in this way requires considerable numerical effort to reach convergence at each time step.

4.3.2 Convective Heat Transfer In the Borehole

Convective heat transfer within the borehole, particularly at the borehole wall has been thought to be of significance in the overall borehole heat transfer. Accordingly some effort has been made to apply appropriate convection correlations to each surface with due regard for variations in surface roughness.

Literature review of convection correlations for pipe flows suggests that the difference between the concentric and eccentric pipe cases may not be significant (Bhatti and Shah 1987). The correlations about eccentric configurations are limited and most are in table form, rather than explicit correlations that can be directly used in the computer code. Accordingly, correlations based on concentric configurations have been applied. In practice, in order to obtain good heat transfer, the annular area in the well is usually smaller than the area inside the tube, so the velocity near the wall is high enough to produce turbulent flow.

Within the well, circular duct correlations have been used to find friction factors. For smooth surfaces, Techo's correlation (Techo *et al.* 1965) has least relative error compared to the PKN¹ empirical formula for $10^4 \leq Re < 10^7$. Colebrook's correlation (Colebrook

¹ PKN(Prandtl, kármán, Nikuradse) correlation: $\frac{1}{\sqrt{f}} = 1.7372 \ln(Re \sqrt{f}) - 0.3946$

1939)² is used when Reynolds number is less than 10^4 . For rough surface, the explicit equation with least relative error compared to Colebrook-White empirical formula is given by Chen in 1979 (Bhatti and Shah 1987). These correlations are:

$$\frac{1}{\sqrt{f}} = 1.7372 \ln \frac{\text{Re}}{1.964 \ln \text{Re} - 3.8215} \quad \text{for smooth surface } 10^4 < \text{Re} < 10^7 \quad (4.34)$$

$$\frac{1}{\sqrt{f}} = 3.48 - 1.7372 \ln \left[\frac{e}{a} - \frac{16.2426}{\text{Re}} \ln A_2 \right] \quad (4.35)$$

for rough surfaces and all values of Re and $\frac{e}{a}$

Where f is fanning friction factor;

Re is Reynolds number, $\text{Re} = \frac{D_h V}{n}$;

D_h is hydraulic diameter (m [ft]);

V is fluid velocity (m/s [ft/sec]);

n is kinematic fluid viscosity (m^2/s [ft²/sec]);

e is height of surface roughness – sand grains (m [ft]);

$$A_2 = \frac{(e/a)^{1.1098}}{6.0983} + \left(\frac{7.149}{\text{Re}} \right)^{0.8981};$$

a is the radius of duct (m [ft]).

In the above formula, more accuracy can be achieved by substituting the laminar equivalent diameter D_l for hydraulic diameter D_h .

$$\frac{D_l}{D_h} = \frac{1 + r^{*2} + (1 - r^{*2}) / \ln r^*}{(1 - r^*)^2} \quad (4.36)$$

where,

$$r^* = \frac{r_i}{r_o};$$

r_o, r_i is the radius of outer and inter pipe respectively (m [ft]);

D_h is hydraulic diameter (4*area/wet perimeter) here: $D_h = 2(r_o - r_i)$ (m [ft]);

Nusselt number correlations for circular ducts have been used to find convection coefficients at both the pipe walls. In these correlations the hydraulic diameter ($D_o - D_i$) is used as the appropriate diameter. The correlation by Gnielinski is used for smooth surfaces such as the discharge and suction tube:

² Colebrook-White correlation: $\frac{1}{\sqrt{f}} = 3.48 - 1.7372 \ln \left(\frac{e}{a} + \frac{9.35}{\text{Re} \sqrt{f}} \right)$

$$Nu = \frac{(f/2)(Re - 1000)Pr}{1 + 12.7(f/2)^{1/2}(Pr^{2/3} - 1)} \quad (4.37)$$

The borehole wall in standing column well is always rougher than the surface of a plastic or steel pipe. The roughness depends on the local geological conditions and drilling method. Increased roughness increases the borehole wall's surface area and promotes local turbulent flow at the rough wall of borehole, which augment the heat transfer. But at the same time, it also brings the increase of friction factor. To deal with this we use the correlation proposed by Bhatti and Shah (1987).

$$Nu = \frac{(f/2)(Re - 1000)Pr}{1 + (f/2)^{1/2}[(17.42 - 13.77Pr_t^{0.8})Re_e^{0.2}Pr^{0.5} - 8.48]} \quad (4.38)$$

Where: Pr is Prandtl number;

$$Pr_t = \begin{cases} 1.01 - 0.09Pr^{0.36} & \text{for } 1 \leq Pr \leq 145 \\ 1.01 - 0.11 \ln Pr & \text{for } 145 < Pr \leq 1800 \\ 0.99 - 0.29(\ln Pr)^{1/2} & \text{for } 1800 < Pr \leq 12500 \end{cases};$$

$$Re_e = \frac{Re \sqrt{f/2}}{D/e};$$

Re_e is roughness Reynolds number,
 e is height of surface roughness – sand grains (m [ft]);
 D is the radius of pipe (m [ft]).

Norris (1971) also found that Nusselt number no longer increased with the increasing roughness. This is because when roughness effects on friction factor become very large ($f/f_{smooth} > 4$), the heat transfer resistance has become essentially a conduction resistance at the surface between the roughness elements.

Free convection may apply at the bottom of the borehole below the suction pipe where the fluid velocities are significantly lower than the rest of the borehole, and also when pump is off. The correlation recommended by Churchill and Chu (1975) for the vertical cylinder has been applied in these cases:

$$Nu = \left\{ 0.825 + \frac{0.387Ra^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}} \right\}^2, \quad \text{for } \frac{D}{L} \geq \frac{35}{Gr_L^{1/4}} \quad (4.39)$$

where,

$$Ra \quad \text{is Rayleigh number} \left(\frac{gb(T_s - T_\infty)L^3}{na} \right)$$

L is the characteristic length L of the cylinder (m [ft]);
 b is expansion coefficient;
 n is kinematic viscosity (m^2/s [ft²/sec]);
 a is thermal diffusivity (m^2/s [ft²/sec]);

Gr_L is Grashof number $\left(\frac{gL^3b\Delta t}{n^2} \right)$.

5.0 Parametric Study

This section describes the methods used to conduct 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-off” times.

The parametric study has been organized using a ‘base case’ and calculating the system performance for this and other cases where a single parameter variation 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

5.1 The Base Case

5.1.1 Building Loads

All the simulations have been made by using building loads calculated for a small office building in Boston, MA (Figure 5.1). The building loads are determined by using building energy simulation software (BLAST, 1986) and the construction is based on a real building in Stillwater, OK. The total area of the building is approximately 1,320 m² (14,205 ft²). The following assumptions have been used to determine the annual building loads:

1. The building is divided into eight different thermal zones.
2. For each zone, a single zone draw through fan system is specified. The total coil loads obtained from system simulation are equal to the loads to be met with ground source heat pump system.

3. The office occupancy is taken as 1 person per 9.3 m² (100 ft²) with a 70% radiant heat gain of 131.9W (450 BTU/hr).
4. A 11.8 W/m² (1.1 W/ft²) of office equipment plug load is used.
5. The lighting loads vary from 10.04W/m² (0.93W/ ft²) to 15.88W/m² (1.47W/ft²) in the different zones.
6. A thermostat set point of 20.0 °C (68.0 °F) during the day (8am-6pm) and 14.4 °C (58.0 °F) during the night is used for all zones in the building. Only heating is provided during the night, depending on the requirement.
7. Schedules for office occupancy, lighting, equipment, and thermostat controls are specified.

The heating and cooling loads for this building are reasonably balanced – see Fig. 5.1. The maximum exiting water temperature (back to the heat pump) occurs during the day of the peak cooling-load (July 15). The minimum temperature back to heat pump occurs during Jan. 15, but does not coincide with the day of peak heating load (Jan 28.). This is caused by the distribution of building load. There are high heating loads for several days leading up to Jan 15 causing a successive reduction in the borehole temperature. In contrast the loads are relatively small immediately before the peak building heating-load on Jan. 28.

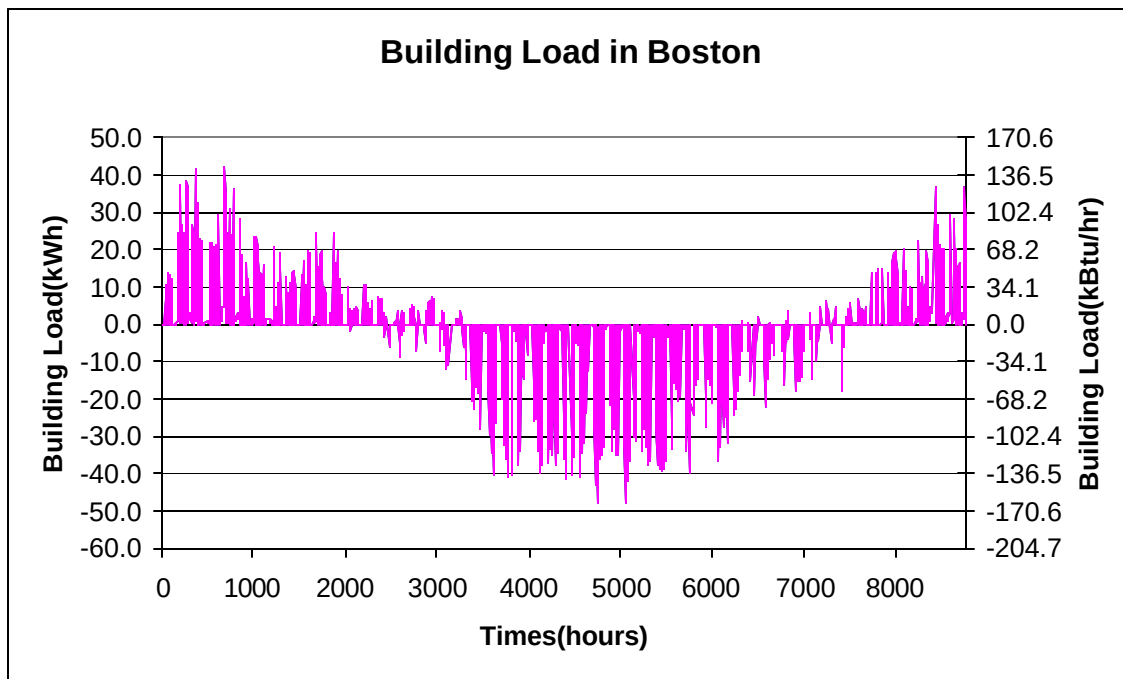


Figure 5.1: Building load of a building in Boston (Positive loads are heating load).

5.1.2 Base Case SCW Design

The design data for the base case well design comes mostly from the well used by Mikler (1993). The geometric arrangement of the well is shown in Figure 5.2. This well has a dip 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 that in the northeast of the U.S. The ground surface temperature used was 11.1°C (52°F), and the natural geothermal gradient is $0.6^{\circ}\text{C}/100\text{m}$ ($0.34^{\circ}\text{F}/100\text{ft}$). The base case thermal and hydraulic properties are taken from the mean values for Karst Limestone found in Table 3.1.

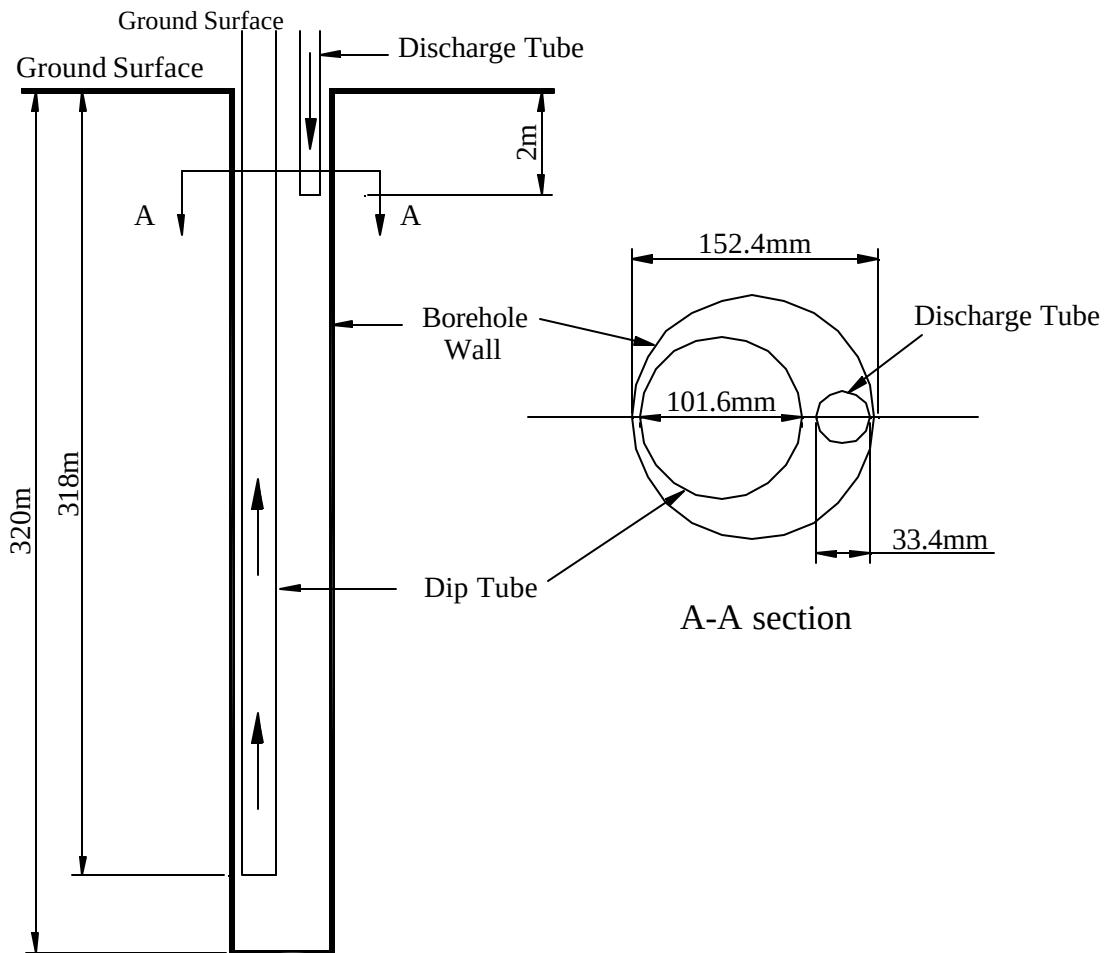


Figure 5.2: A schematic drawing showing the borehole geometric arrangement for the base case.

Table 5.1
Properties of the base case SCW

Parameter	Depth	Diameter	Wall Thickness	Thermal Conductivity	Surface Roughness
Units	m (ft)	mm (in)	m (in)	W/m.°C (Btu/hr.ft.°F)	mm (in)
Borehole	320 (1049.6)	152.4 (6)	-----	-----	1.5 (0.06)
Discharge pipe	2 (6.56)	33.4 (1.3)	3.05 (0.12)	4 (2.31)	1.5 (0.06)
Suction Pipe	318 (1043)	101.6 (4)	6.35 (0.25)	0.1 (0.0578)	1.5 (0.06)

5.2 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.

The total number of cases has been limited due to the considerable length of time each calculation takes – approximately 14 days on the fastest available PCs. This effort has required up to six computers running continually for more than 24 weeks. Consequently it has not been feasible to make calculations for all parameter value combinations – only a base case with one parameter varied at a time. The parameter values for the different cases in addition to the base case are shown in Table 5.2.

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, when water temperature back to HP is lower than 5.83°C (42.5°F), bleed is started. When the water temperature back to HP is higher than 8.6 °C (47.5°F), bleed is stopped. In summer, bleed is started when water temperature back to HP is higher than 29.2 °C (84.5°F), and stopped when water temperature back to HP is lower than 26.4 °C (79.5°F)³.
2. Temperature-difference control: The temperature difference (ΔT) between water back to and from HP was used as a controlled parameter. The temperature difference (ΔT) was set to give the same number of hours of operation as the deadband bleed control case: 5.6°C (42.1°F).

In both cases the rate of bleed was 10%.

³ Personal communication with Mr. Carl D. Orio in Water and Energy System Corporation.

R&D Studies applied to SCW design

Parametric Study

Table 5.2

Parametric study parameter values. Values changed from the base case are highlighted with shading

Parameter		Thermal conductivity of rock	Natural geothermal gradients of rock	Specific heat capacity of rock	Hydraulic conductivity of rock	Surface roughness	Borehole diameter	Casing depth	Dip tube diameter	Borehole length	Bleed rate	Porosity	Thermal conductivity of dip tube
No.	Case	W/m°C (Btu/hr-ft-°F)	°C/100m (°F/100m)	J/m ³ °C (Btu/ft ³ -°F)	m/s (gal/day/ft ²)	m (in)	m (in)	m (in)	m (in)	m (ft)	(%)	(.)	W/m°C (Btu/hr-ft-°F)
1	Base	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	0	0.275	0.1 (0.0577)
2	kt2	2.5 (1.44)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	0	0.275	0.1 (0.0577)
3	kt3	4.3 (2.48)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	0	0.275	0.1 (0.0577)
4	s2	3 (1.73)	0.6 (0.329)	2.13E+06 (31.77)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	0	0.275	0.1 (0.0577)
5	s3	3 (1.73)	0.6 (0.329)	5.50E+06 (82.03)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	0	0.275	0.1 (0.0577)
6	n2	3 (1.73)	0.3 (0.17)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	0	0.275	0.1 (0.0577)
7	n3	3 (1.73)	1.8 (0.99)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	0	0.275	0.1 (0.0577)
8	kh2	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	1.00E-04 (211.8)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	0	0.275	0.1 (0.0577)
9	kh3	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	1.00E-06 (2.118)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	0	0.275	0.1 (0.0577)
10	h2	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	3.00E-04 (0.01)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	0	0.275	0.1 (0.0577)
11	h3	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	9.00E-03 (0.35)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	0	0.275	0.1 (0.0577)
12	h4	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	3.00E-03 (0.12)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	0	0.275	0.1 (0.0577)

R&D Studies applied to SCW design

Parametric Study

Table 5.2 Continued

Parametric study parameter values. Values changed from the base case are highlighted with shading

Parameter		Thermal conductivity of rock	Natural geothermal gradients of rock	Specific heat capacity of rock	Hydraulic conductivity of rock	Surface roughness	Borehole diameter	Casing depth	Dip tube diameter	Borehole length	Bleed rate	Porosity	Thermal conductivity of dip tube
No.	Case	W/m°C (Btu/hr-ft-°F)	°C/100m (°F/100m)	J/m ³ °C (Btu/ft ³ -°F)	m/s (gal/day/ft ²)	m (in)	m (in)	m (in)	m (in)	m (ft)	(%)	()	W/m°C (Btu/hr-ft-°F)
13	d2	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1398 (5.5)	0 (0)	0.1016 (4)	320 (1050)	0	0.275	0.1 (0.0577)
14	d3	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1778 (7)	0 (0)	0.1016 (4)	320 (1050)	0	0.275	0.1 (0.0577)
15	d4	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.0762 (3)	320 (1050)	0	0.275	0.1 (0.0577)
16	d5	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1143 (4.5)	320 (1050)	0	0.275	0.1 (0.0577)
17	d6	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	0	0.275	0.4 (0.2308)
18	c2	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	160 (525)	0.1016 (4)	320 (1050)	0	0.275	0.1 (0.0577)
19	c3	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	90 (295)	0.1016 (4)	320 (1050)	0	0.275	0.1 (0.0577)
20	c4	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	60 (197)	0.1016 (4)	320 (1050)	0	0.275	0.1 (0.0577)
21	b1	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	10	0.275	0.1 (0.0577)
22	b2	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	15	0.275	0.1 (0.0577)
23	b3	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	20	0.275	0.1 (0.0577)
24	b4	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	2.5	0.275	0.1 (0.0577)
25	b5	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	5	0.275	0.1 (0.0577)

R&D Studies applied to SCW design

Parametric Study

Table 5.2 Continued

Parametric study parameter values. Values changed from the base case are highlighted with shading

Parameter		Thermal conductivity of rock	Natural geothermal gradients of rock	Specific heat capacity of rock	Hydraulic conductivity of rock	Surface roughness	Borehole diameter	Casing depth	Dip tube diameter	Borehole length	Bleed rate	Porosity	Thermal conductivity of dip tube
No.	Case	W/m°C (Btu/hr-ft-°F)	°C/100m (°F/100m)	J/m ³ °C (Btu/ft ³ -°F)	m/s (gal/day/ft ²)	m (in)	m (in)	m (in)	m (in)	m (ft)	(%)	()	W/m°C (Btu/hr-ft-°F)
26	L1	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	240 (787)	0	0.275	0.1 (0.0577)
27	L2	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	280 (919)	0	0.275	0.1 (0.0577)
28	L3	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	360 (1181)	0	0.275	0.1 (0.0577)
29	L4	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	400 (1312)	0	0.275	0.1 (0.0577)
30	kt4	1.5 (0.865)	0.6 (0.329)	2.13E+06 (31.77)	5.00E-07 (1.059)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	0	0.1	0.1 (0.0577)
31	kt5	5 (2.88)	0.6 (0.329)	2.20E+06 (32.81)	1.50E-06 (3.176)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	0	0.05	0.1 (0.0577)
32	kh4	4 (2.30)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-10 (0.00148)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	320 (1050)	0	0.18	0.1 (0.0577)
33	L1_bt1	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	240 (787)	10	0.275	0.1 (0.0577)
34	L1_bt3	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	240 (787)	5	0.275	0.1 (0.0577)
35	L1_bt1-t	3 (1.73)	0.6 (0.329)	2.70E+06 (40.27)	7.00E-05 (148.23)	1.50E-03 (0.06)	0.1524 (6)	0 (0)	0.1016 (4)	240 (787)	10	0.275	0.1 (0.0577)

Note:

Rock type

Case kt4

Dolomite

Case kt5

Fractured igneous and metamorphic

Case kh4

Sandstone

all the other cases

Karst limestone

5.3 System Energy Calculations

For each case in the parametric study the annual energy consumption of the heat pump and well pump have been calculated. Fluid temperatures and well pump operating hours are output from the annual system simulations. To calculate the energy consumption the pump head, power consumption and hourly heat pump power consumption also have to be calculated. This procedure is described below.

5.3.1 System pressure drop without bleed

A schematic of the pipework system applicable to cases without bleed is shown in Figure 5.3.

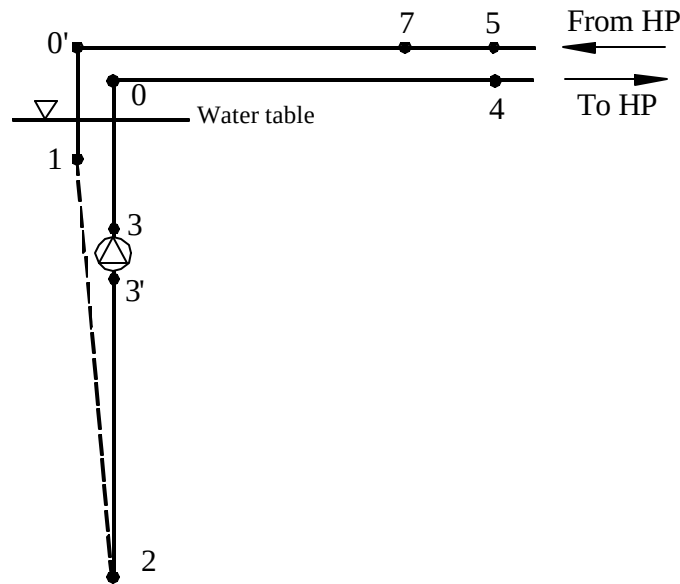


Figure 5.3 Pipe system schematic for cases without bleed .

We assume that p_w is the atmosphere pressure at the water table, and the elevation here is z_w . The mechanical energy equation can be applied to a number of points in the system and used to find the pump head.

Between the water table section and node 1 (neglecting frictional losses):

$$p_w + rgz_w = p_1 + \frac{rv_1^2}{2} + rgz_1 \quad (5.1)$$

Rearranging gives,

$$p_1 = p_w - rgz_w - \frac{rv_1^2}{2} - rgz_1 \quad (5.1a)$$

Between water table section and node 2:

$$p_w + rgz_w = p_2 + \frac{rv_2^2}{2} + rgz_2 + \Delta p_{1-2loss} \quad (5.2)$$

Rearranging gives,
$$p_2 = p_w - rgz_w - \frac{rv_2^2}{2} - rgz_2 - \Delta p_{1-2loss} \quad (5.2a)$$

Between water table section and 3' node:

$$p_w + rgz_w = p_{3'} + \frac{rv_{3'}^2}{2} + rgz_{3'} + \Delta p_{2-3'loss} \quad (5.3)$$

Rearranging gives,
$$p_{3'} = p_w + rgz_w - \frac{rv_{3'}^2}{2} - rgz_{3'} - \Delta p_{2-3'loss} \quad (5.3a)$$

Between node 3 and node 1

$$p_3 + \frac{rv_3^2}{2} + rgz_3 = p_1 + \frac{rv_1^2}{2} + rgz_1 + \Delta p_{3-4-5-1loss} \quad (5.4)$$

Now substituting $p_w = p_1 + \frac{rv_1^2}{2} + rgz_1 - rgz_w$ into the equation (5.4)

$$p_3 = p_w + rgz_w - \frac{rv_3^2}{2} - rgz_3 + \Delta p_{3-4-5-1loss} \quad (5.4a)$$

Assuming $z_3 = z_{3'}$ and $v_3 = v_{3'}$, thus the total dynamic head for the pump is

$$H = p_3 - p_{3'} = \Delta p_{3-4-5-1loss} + \Delta p_{2-3'loss} \quad (5.5)$$

5.3.2 System pressure drop with bleed

A schematic of the pipework system applicable to cases with bleed is shown in Figure 5.3.

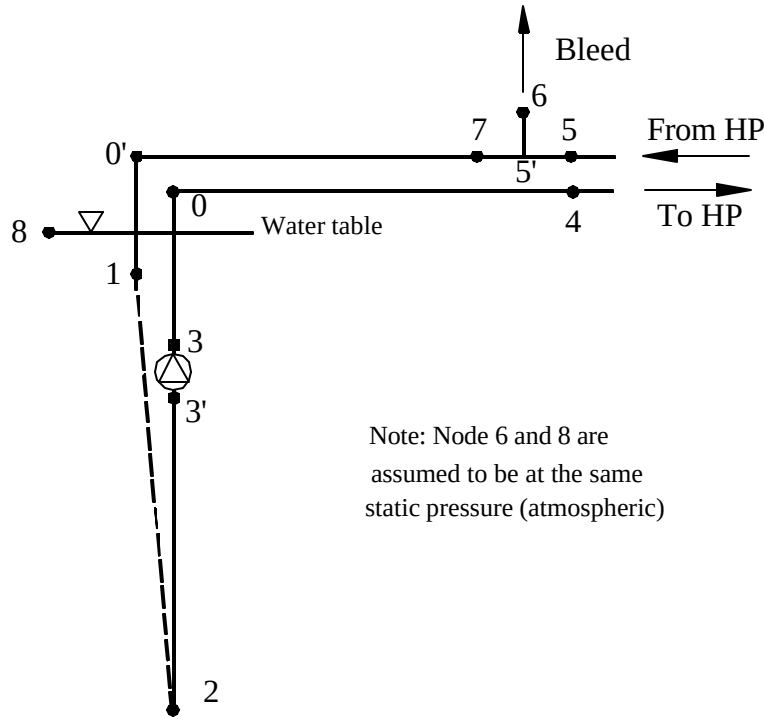


Figure 5.3 pipe system schematic for cases with bleed .

Bernoulli's equation can be applied to a number of points in the system and used to find the pump head.

Between water table section and node 3':

$$p_w + rgz_w = p_{3'} + \frac{rv_{3'}^2}{2} + rgz_{3'} + \Delta p_{w-3'loss} \quad (5.6)$$

Between node 3 and node 5':

$$p_3 + \frac{rv_3^2}{2} + rgz_3 = p_{5'} + \frac{rv_{5'}^2}{2} + rgz_{5'} + \Delta p_{3-5'loss} \quad (5.7)$$

Applying an energy balance at node 5':

$$m \cdot (p_{5'} + \frac{rv_{5'}^2}{2} + rgz_{5'}) = m \cdot (1 - bleedrate) \cdot (p_w + rgz_w + \Delta p_{5'-wloss}) + m \cdot bleedrate \cdot (p_6 + rgz_6 + \Delta p_{5'-6loss}) \quad (5.8)$$

where m is the mass flow rate and *bleed rate* is the fractional (normalized) rate of bleed.

The pressure loss from node 5' to 6 is equal to the pressure loss from node 5' to the water table. Applying a mass balance at node 5' and a pressure balance enables the loss from 5' to 6 to be calculated for a given flow rate and return pipe size.

We assume that p_w is the atmosphere pressure at the water table, and the elevation here is z_w and is used as the datum elevation ($z_w = 0$). The aboveground pipework is assumed to be at the same elevation, z_{ground} . If the water level is used as a datum ($z_w = 0$) then $z_6 = z_{ground} = h_{watertable}$. Assuming $p_6 = p_w$, $z_3 = z_{3'}$ and $v_{5'} = v_3 = v_{3'}$, the total dynamic head for the pump can be shown to be,

$$H = p_3 - p_{3'} = \Delta p_{5'-6loss} + bleedrate \cdot rgh_{watertable} + \Delta p_{8-5'loss} \quad (5.9)$$

In the foregoing equations (5.1) to (5.9)

p is static pressure (Pa);

$\frac{rv^2}{2}$ is velocity pressure (Pa);

rgz is elevation pressure (Pa);

Δp is total pressure loss (friction) (Pa);

H is total dynamic head for the water pump (Pa);

bleedrate is the normalized bleed rate in the system (-);

5.3.3 Heat pump model

To match the peak building loads of the hypothetical building two CLIMATEMASTER HL Horizontal 072 heat pumps (water to air heat pump) were selected. Curve fits describing capacity vs. entering water temperature and power consumption vs. entering water temperature, at a range of flow-rates, were derived from the catalogue data. The following functions were used

R&D Studies applied to SCW design

Parametric Study

$$HP_capacity = 22410.37 + 1122.66 * EWT - 3.0345 * EWT^2 \quad (\text{Heating mode})$$

$$HP_capacity = 97442.70 - 332.76 * EWT - 0.1491 * EWT^2 \quad (\text{Cooling mode})$$

$$HP_power = 6130.83 - 16.30 * EWT + 0.3305 * EWT^2 \quad (\text{Heating mode})$$

$$HP_power = 3198.09 + 39.03 * EWT + 0.0247 * EWT^2 \quad (\text{Cooling mode})$$

As the calculation time steps were 6-hourly it was also necessary to calculate a 'run time fraction' for each step. It was assumed that both heat pumps run at all times and that the heat pump performance only changed with entering water temperature.

5.3.4 Circulating pump model

To calculate the pump power consumption, a pump with sufficient capacity to match the system flow and pressure drop was selected. A MUNRO 4in. submersible well pump (18GPM series) was chosen. This pump is capable of meeting the flow and head requirements in bleed and non-bleed modes of operation.

The following equation can be used to calculate the power consumption of circulating water pump:

$$w = \frac{gQH}{h} \quad (5.10)$$

Where: g = rg r is water density (kg/m³);

Q is volume flow rate (m³/s);

H is the total dynamic head (m);

h is efficiency of the circulating water pump (pump and motor),
taken as 0.65 during this calculation (Rafferty ,1998);

w is the power consumption of the circulating water pump(W).

5.3.5 Frictional Pressure Losses

Frictional pressure losses are calculated for each section of the pipework. Losses for straight pipe are calculated from the moody friction factor, and fitting losses from standard loss coefficients. To calculate the total pressure loss:

$$\Delta p_m = \sum \left(f \frac{L}{D} + K \right) \frac{V^2}{2g} \quad (5.11)$$

Where Δp_m is total pressure loss(fitting +friction) (m);

f is Moody friction factor;

L is length of the given pipe section(m);

D is diameter of the given pipe (m);

K is resistance coefficient;

V is mean velocity in the given pipe(m/s);

g is acceleration due to gravity (m/s²).

R&D Studies applied to SCW design

Parametric Study

For Moody friction factor, the following correlations are used during the calculation (Techo et al 1965, Colebrook, 1939, Chen, 1979).

$$\frac{1}{\sqrt{f}} = 1.7372 \ln \frac{\text{Re}}{1.964 \ln \text{Re} - 3.8215} \quad \text{for smooth surfaces } 10^4 \leq \text{Re} < 10^7 \quad (5.12)$$

$$\frac{1}{\sqrt{f}} = 1.5635 \ln\left(\frac{\text{Re}}{7}\right) \quad \text{for smooth surfaces } \text{Re} < 10^4 \quad (5.13)$$

$$\frac{1}{\sqrt{f}} = 3.48 - 1.7372 \ln\left[\frac{e}{a} - \frac{16.2426}{\text{Re}} \ln A_2\right] \quad \text{for rough surfaces apply to all the values of}$$

$$\text{Re and } \frac{e}{a} \quad (5.14)$$

Where f is fanning friction factor;

$$\text{Re is Reynolds number, } \text{Re} = \frac{D_h V}{n};$$

D_h is hydraulic diameter (m [m]);

V is fluid velocity (m/s [ft/sec]);

n is kinematic fluid viscosity (m²/s [ft²/sec]);

e is height of surface roughness – sand grains (m [ft]);

$$A_2 = \frac{(e/a)^{1.1098}}{6.0983} + \left(\frac{7.149}{\text{Re}}\right)^{0.8981};$$

a is the radius of pipe (m [ft]).

Pipe fittings are shown in Figure 5.4. Fitting resistance coefficients were taken from the ASHRAE tables (ASHRAE 2001).

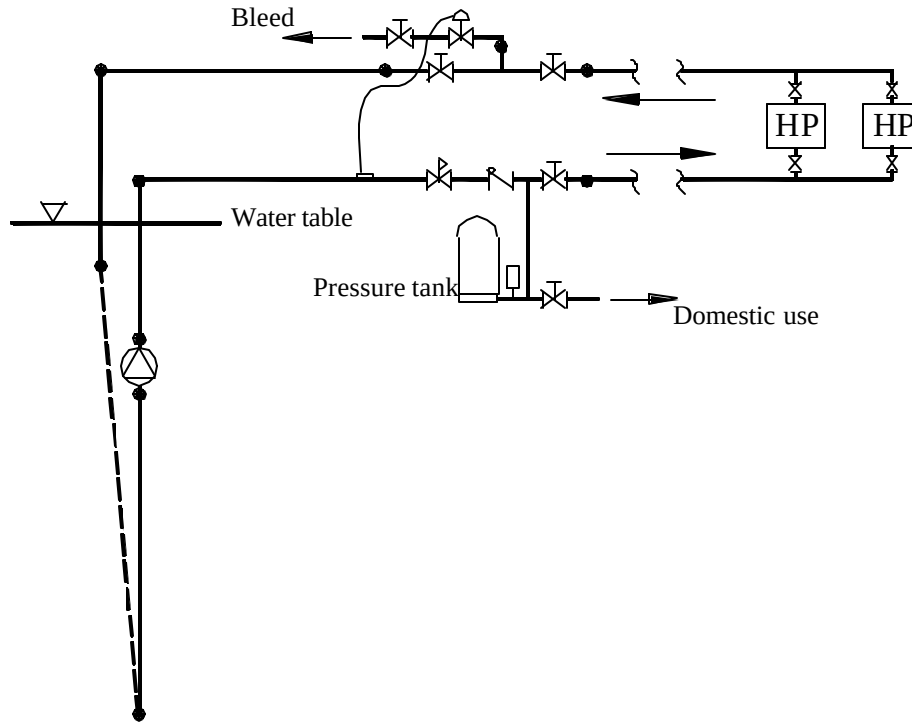


Figure 5.4 Schematic diagram of the pipework system showing the arrangement of fittings.

5.3.6 Electricity costs

The cost of energy consumed by the well pump and heat pump has been calculated using the monthly schedule in Table 5.3 (commercial rate), which was applicable to the state of Massachusetts in the year 2000.

Table 5.3
Electric utility monthly average cost per Kilowatt-hour for Massachusetts in 2000
(cents per kilowatt-hour)*

Building type	Jan.	Feb.	March	April	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Residential	10.2	9.7	10.2	11.0	11.1	11.3	11.0	10.8	11.5	11.2	11.1	11.0
Commercial	7.8	7.5	7.8	8.5	8.7	9.8	10.2	10.1	10.7	9.5	8.6	8.7

*data from http://www.eia.doe.gov/cneaf/electricity/page/at_a_glance/sales_tabs.html

6.0 Parametric Study Results

Results of the calculations are presented in this section. Detailed results from a particular case showing the calculated ground-water flow field and head distribution is discussed in subsection 6.1. Results from the parametric study are presented in subsection 6.2.

6.1 Calculated Ground-Water Flows and Head Distribution

Some sample results from the calculation of head and flow in the rock surrounding the borehole are shown in Figs. 6.0-6.2. In all these figures the axis of the borehole is at the left-hand edge. Figs 6.0 and 6.1 show the mass flow vectors under normal operation and bleed conditions respectively.

In Fig.6.0 the general circulation of ground water through the rock from the area near the discharge at the top of the borehole to the suction can be seen (the vectors show a clockwise flow pattern in the plot). It should be noted that these mass flows are several orders of magnitude lower than the main vertical flow in the borehole annulus. A neutral point approximately halfway down the length of the borehole can be seen in normal operating conditions (Fig.6.0). Above this point there is flow from the borehole into the rock, and below this point the flow is into the borehole from the rock.

Figure 6.1 shows the ground-water flow for the same case but during a period of bleed operation. In this case, comparing with Fig 6.0, the flow near the discharge (at the top left) is reduced. Also, rather than the recirculating flow pattern, flow can be seen to be radially inwards from the far field (the vectors on the right are all pointing left towards the borehole).

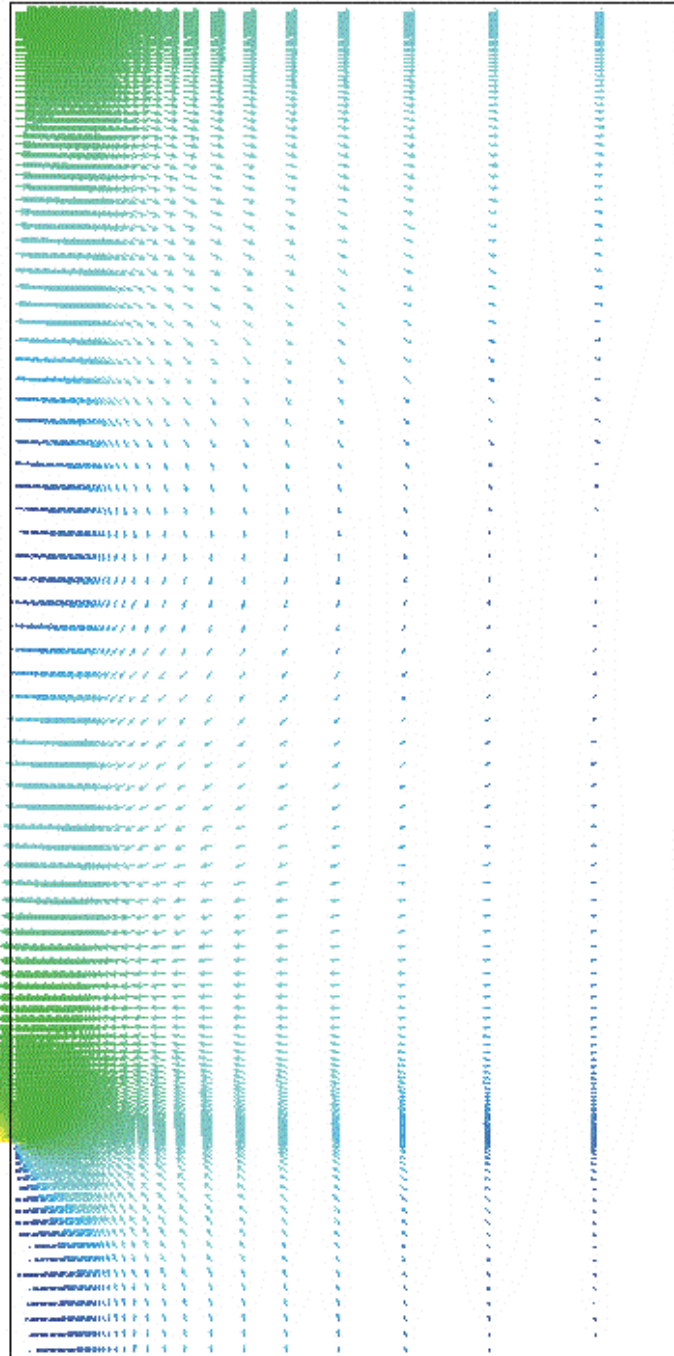


Figure 6.0: Mass flow vectors in normal operation (no bleed). The vectors are enlarged for clarity. The maximum flow (near the suction inlet) is 0.1803E-4 m/s.

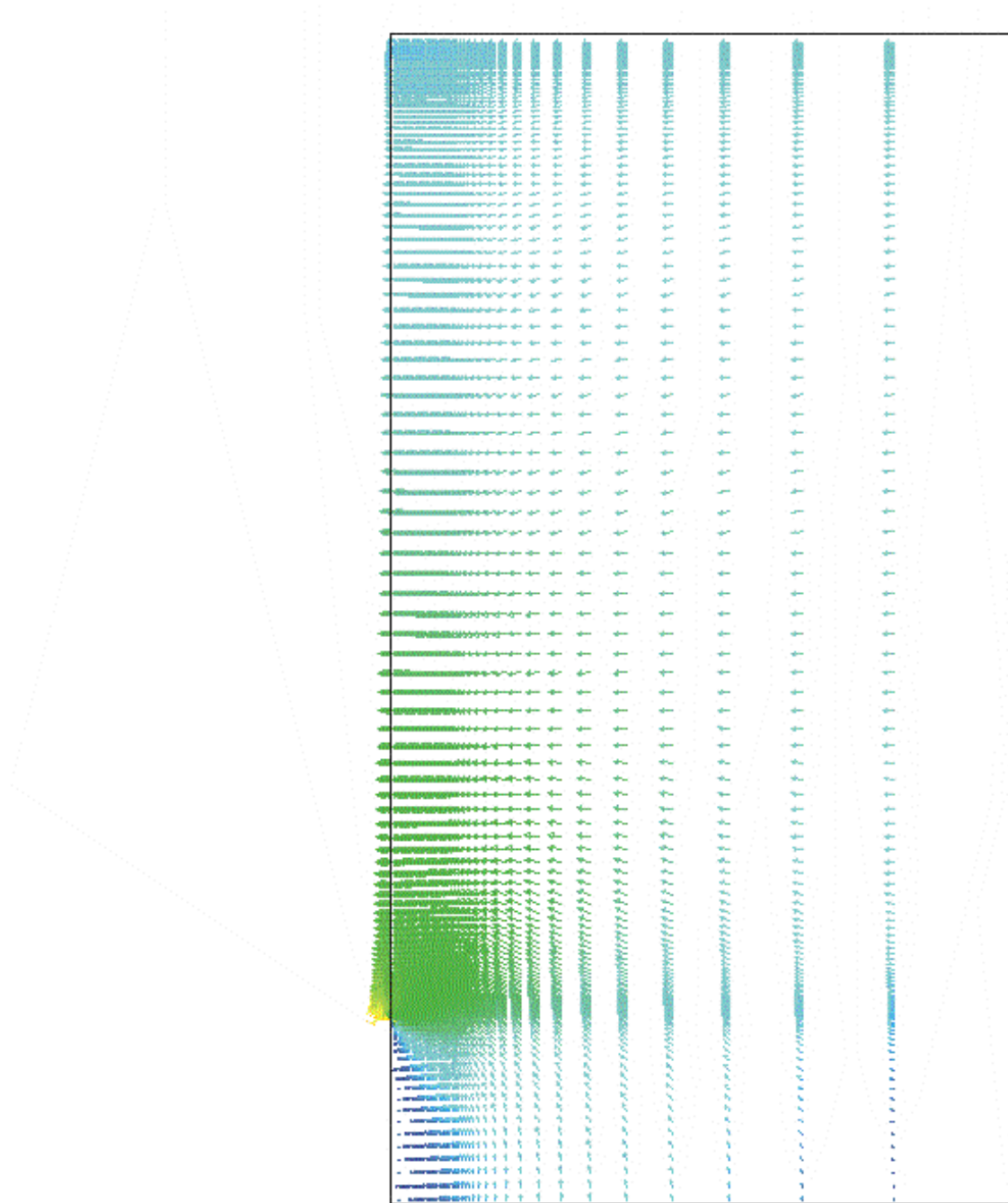


Figure 6.1: Mass flow vectors in bleed operation (25% bleed). The vectors are enlarged for clarity. The maximum flow (near the suction inlet) is $0.1803\text{E-}4$ m/s.

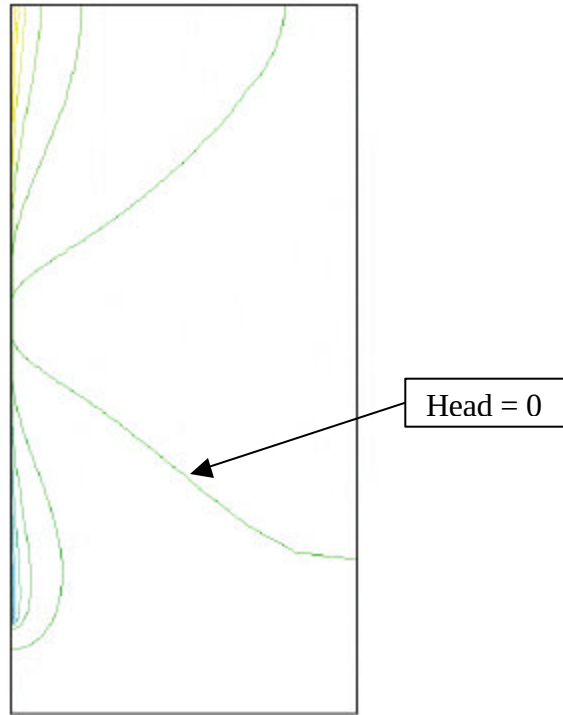


Figure 6.2: Head Contours in normal operation (no bleed).

Figure 6.2 shows the (dynamic) head distribution in normal operation. In this figure the neutral point is indicated by the zero head contour intersecting with the borehole wall approximately halfway down its length.

Figures 6.3 and 6.4 show borehole operating temperatures over the length of the borehole. Fig. 6.3 represents data on Jan 28, when peak heating-load occurs, and Fig 6.4 on July 15 at peak cooling demand. The temperature in the dip tube (suction temperature) variation along the borehole can be seen to be non-linear. This variation in temperature is due to heat transfer between the fluid in the suction pipe and the surrounding fluid in the borehole. This heat transfer results in a depression of the exiting fluid temperature during heating mode, and an increase in temperature during cooling. This heat transfer is therefore generally detrimental to SCW efficiency.

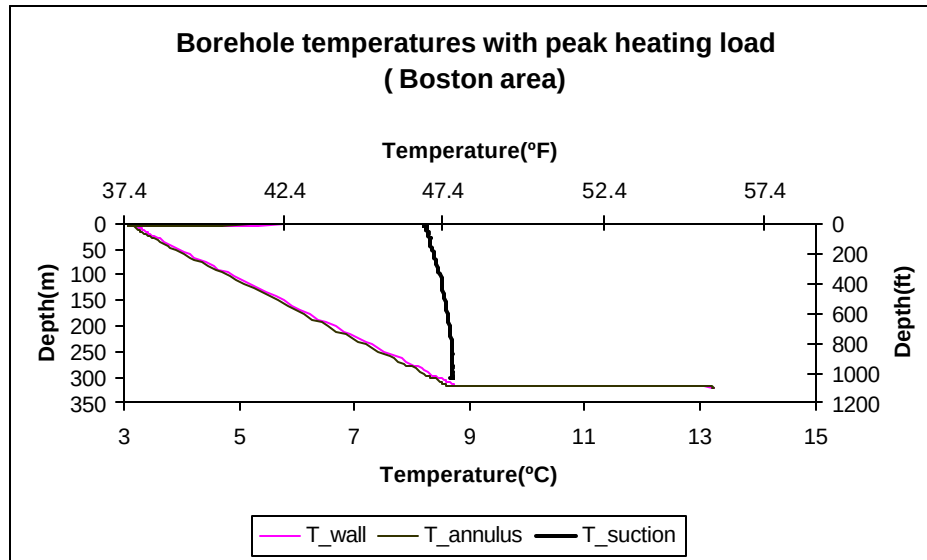


Figure 6.3: Borehole temperatures when peak heating load occurs.

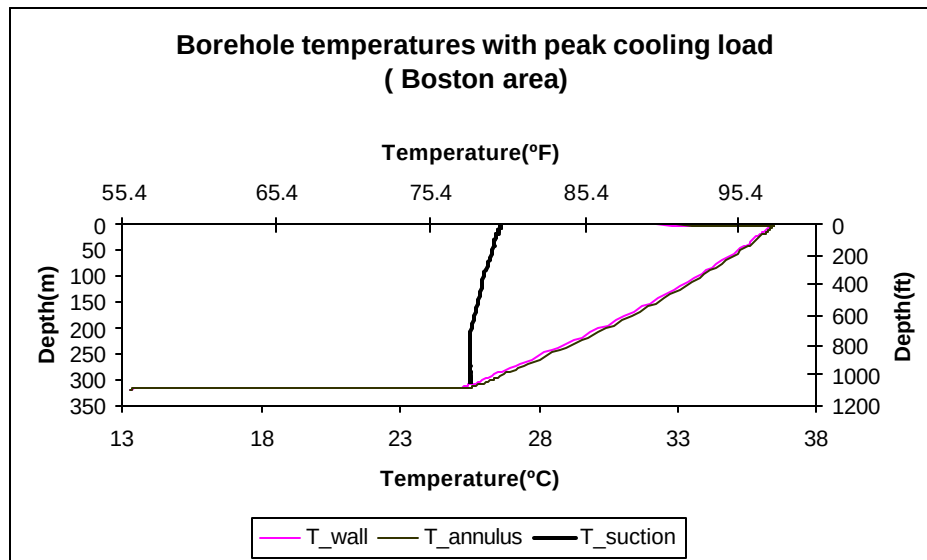


Figure 6.4: Borehole temperatures when peak cooling load occurs.

Figure 65 shows the suction and discharge temperature over the whole year of operation, along with the building loads. The difference between suction and discharge temperatures coincides with the building loads shown in the lower part of Figure 6.5. Notice that the fluid temperatures at the end of the year are very similar to those at the start of the year. This is due to the balanced nature of the building load.

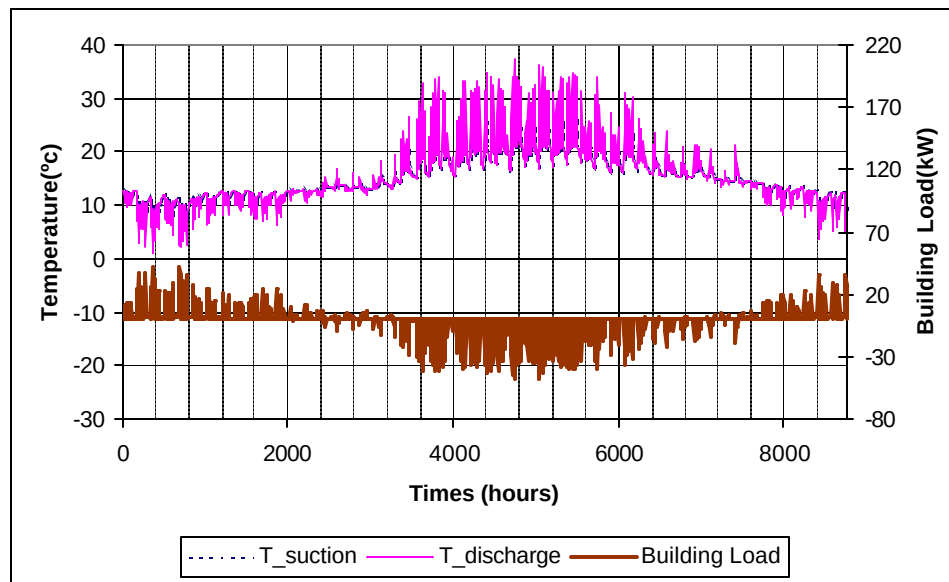


Figure 6.5: Borehole suction and discharge temperatures and building loads for base case.

6.2 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 parameter values. Accordingly, in the presentation of the results we show firstly how the maximum and minimum exiting fluid temperatures from the standing column well vary with a single parameter. These data are given in tabular form in Table 6.1. These temperatures have also been plotted against each parameter and are discussed in the subsections 6.2.1-6.2.15.

In an attempt to correlate changes in parameter values with effective changes in design borehole length a number of simulations were made using the base case but with different borehole lengths. The results of these calculations are shown in Fig. 6.6 in terms of the corresponding minimum and maximum temperatures. 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 parameter variation has in terms of the design well depth. This data is presented in the right-hand column of Table 6.1.

The method used to calculate and apply the relationship between temperatures and equivalent borehole length is described as follows. The linear correlations between the fluid temperatures and length are assumed to have the form:

$$EWT_{\max} = C_1 + C_2 \cdot L \quad (6.1)$$

$$EWT_{\min} = C_3 + C_4 \cdot L \quad (6.2)$$

The constants found from the data shown in Figure 6.6 have the values:

$$C_1 = 46.67, C_2 = -0.0604;$$

$$C_3 = -5.78, C_4 = 0.00372.$$

The design conditions are:

$$\text{Summer: } EWT_{\max} = 32^\circ\text{C},$$

$$\text{Winter: } EWT_{\min} = 6^\circ\text{C}.$$

$$L_{\text{design}} = 317\text{m}$$

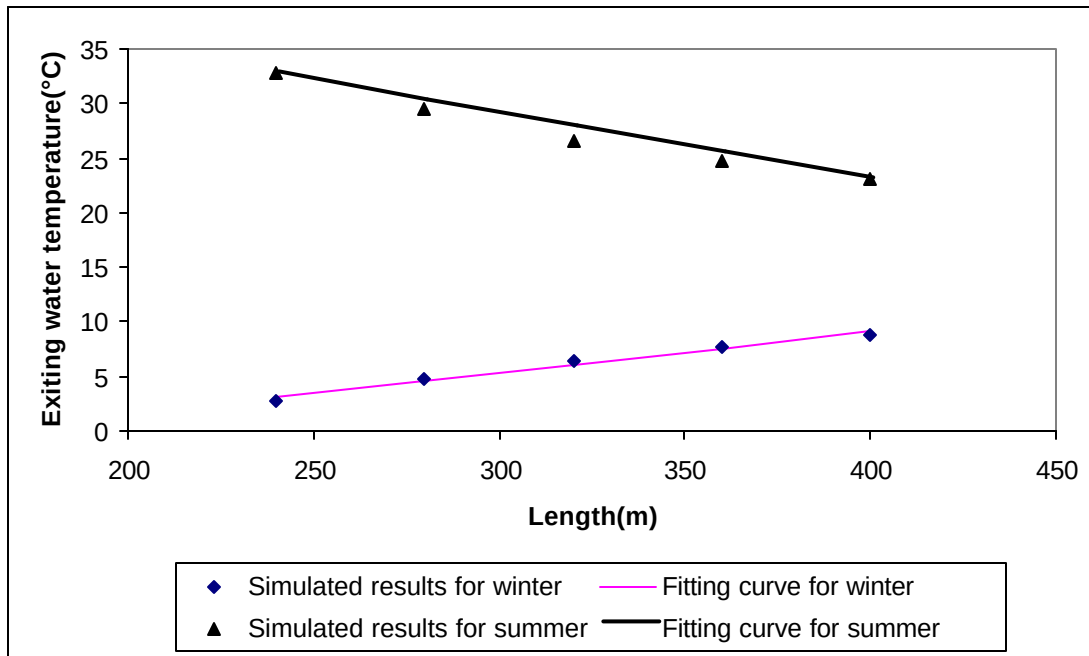


Figure 6.6: Relationship between EWT and length of borehole.

For other cases, we assume the slopes of all the curves are the same with the one of base case, so that:

$$EWT_{\max,i} = C_{1,i} + C_2 \cdot L \quad (6.3)$$

$$EWT_{\min,i} = C_{3,i} + C_4 \cdot L \quad (6.4)$$

The constants $C_{1,i}$, $C_{3,i}$ for each case are obtained from maximum/minimum EWT difference between the given case and base case. We can then use equations 6.3 and 6.4 to find the equivalent length.

Table 6.1

Parametric study results – effect of parameter variations on minimum and maximum exiting fluid temperatures and design length.

Parameter Varied	Case name	Parameter Values (Units)	Max. Exiting Fluid Temperature °C (°F)	Min. Exiting Fluid Temperature °C (°F)	Equivalent Design Length m (ft)
Thermal conductivity		W/m°C (Btu/hr.ft.°F)			
	kt2	2.5 (1.44)	27.9 (82.3)	5.7 (42.3)	331 (1086)
	Base	3.0 (1.73)	26.6 (79.9)	6.4 (43.6)	317 (1040)
	kt3	4.3 (2.48)	23.5 (74.3)	7.8(46.0)	281 (922)
Natural geothermal gradients		°C/100m (°F/100ft)			
	n2	0.3 (0.17)	26.6 (79.9)	6.42 (43.6)	317 (1040)
	Base	0.6 (0.33)	26.6 (79.9)	6.44 (43.6)	317 (1040)
	n3	1.8 (1.0)	30.0 (85.9)	9.58 (49.3)	298 (978)
Specific heat capacity		J/m³°C (Btu/ft³.°F)			
	s2	2.13E+06 (31.8)	27.0 (80.7)	6.24 (43.2)	322 (1056)
	Base	2.70E+06 (40.3)	26.6 (79.9)	6.44 (43.6)	317 (1040)
	s3	5.50E+06 (82.0)	25.3 (77.6)	7.15(44.9)	297 (974)
Borehole diameter		m (in)			
	d2	0.1398 (5.5)	26.2 (79.2)	6.31 (43.4)	320 (1050)
	Base	0.1524 (6)	26.6 (79.9)	6.44 (43.6)	317 (1040)
	d3	0.1778 (7)	27.5 (81.4)	7.08 (44.7)	281 (922)
Bleed rate (two-year operation)		Bleed rate (%)			
	Base	0	26.6 (79.9)	6.44 (43.6)	317 (1040)
	b4	2.5	20.9 (69.7)	9.11 (48.4)	245 (804)
	b5	5.0	17.4 (63.3)	10.9 (51.6)	197 (646)
	b1	10.0	15.0 (59.0)	11.4 (52.5)	184 (604)
	b2	15.0	14.1 (57.4)	11.5 (52.7)	181 (594)
	b3	20.0	13.7 (56.6)	11.6 (52.8)	179 (587)
Casing depth		m (ft)			
	Base	0 (0)	26.6 (79.9)	6.44 (43.6)	317 (1040)
	c4	60 (197)	26.9 (80.4)	6.54 (43.8)	320 (1050)
	c3	90 (295)	27.1 (80.8)	6.44 (43.6)	317 (1040)
	c2	160 (525)	27.3 (81.2)	6.33 (43.4)	314 (1030)
Surface roughness		m (in)			
	Base	1.50E-03 (0.06)	26.6 (79.9)	6.44 (43.6)	317 (1040)
	h2	3.00E-04 (0.01)	27.0 (80.5)	6.06 (42.9)	327 (1073)
	h4	3.00E-03 (0.12)	26.8 (80.2)	6.37 (43.5)	319 (1047)
	h3	9.00E-03 (0.35)	26.2 (79.2)	6.51 (43.7)	315 (1033)

Table 6.1 Continued

Parametric study results – effect of parameter variations on minimum and maximum exiting fluid temperatures and design length.

Parameter Varied	Case name	Parameter Values	Max. Exiting Fluid Temperature °C (°F)	Min. Exiting Fluid Temperature °C (°F)	Equivalent Design Length m (ft)
Hydraulic conductivity		m/s (gal/day/ft²)			
	kh3	1.00E-06 (2.118)	25.0 (77.2)	7.25 (45.0)	295 (968)
	Base	7.00E-05 (148.23)	26.6 (79.9)	6.44 (43.6)	317 (1040)
	kh2	1.00E-04 (211.8)	24.6 (76.4)	7.09 (44.8)	299 (981)
Dip tube diameter		m (in)			
	d4	0.0762 (3)	26.5 (79.6)	6.54 (43.8)	314 (1030)
	Base	0.1016 (4)	26.6 (79.9)	6.44 (43.6)	317 (1040)
	d5	0.1143 (4.5)	26.8 (80.2)	6.33 (43.4)	320 (1050)
	d6	0.1016 (insulation different)	28.5 (83.3)	5.56 (42.0)	340 (1115)
Depth of borehole		m (ft)			
	L1	240 (787)	32.6 (91.1)	2.81 (37.1)	
	L2	280 (919)	29.4 (85.0)	4.78 (40.6)	
	Base	320 (1050)	26.6 (79.9)	6.44 (43.6)	317 (1040)
	L3	360 (1181)	24.6 (76.4)	7.74 (45.9)	
	L4	400 (1321)	23.2 (73.7)	8.76 (47.8)	
Different rock type		Rock type			
	Base	Karst limestone	26.6 (79.9)	6.44 (43.6)	317 (1040)
	kt4	Dolomite	34.4 (93.9)	4.23 (39.6)	376 (1234)
	kt5	Fractured igneous and metamorphic	19.4 (67.0)	9.38 (48.9)	238 (781)
	kh4	Sandstone	21.3 (70.3)	8.57 (47.4)	259 (850)
Bleed control		Bleed rate (%)			
	L1	0	32.6 (91.1)	2.81 (37.1)	
	L1_bt3	5.0 (Dead-band)	31.3 (88.3)	3.66 (38.6)	
	L1_bt1	10.0 (Dead-band)	32.0 (89.6)	3.49 (38.3)	
	L1_bt1_t	10.0 (Temperature difference)	21.4 (70.5)	5.53 (42.0)	
Reverse		Reverse			
	No reverse	Base	26.6 (79.9)	6.44 (43.6)	317 (1040)
	Reverse	Reverse A	25.8 (78.4)	5.66 (42.2)	335 (1099)

Table 6.1 Continued

Parametric study results – effect of parameter variations on minimum and maximum exiting fluid temperatures and design length.

Parameter Varied	Case name	Parameter Values	Max. Exiting Fluid Temperature °C (°F)	Min. Exiting Fluid Temperature °C (°F)	Equivalent Design Length m (ft)
Bleed rate (one-year operation)		Bleed rate (%)			
	Base	0	26.6 (79.9)	6.44 (43.6)	253 (830)
	b4(2)	2.5	20.5 (68.9)	8.79 (47.8)	211 (692)
	b5(2)	5.0	16.9 (62.3)	10.4 (50.7)	187 (614)
	b1(2)	10.0	14.5 (58.1)	11.3 (52.3)	176 (577)
	b2(2)	15.0	13.8 (56.8)	11.7 (53.0)	174 (571)
	b3(2)	20.0	13.4 (56.0)	11.8 (53.2)	253 (830)

6.2.1 Thermal conductivity

Figure 6.7 shows the variation of the minimum and maximum exiting fluid temperatures with rock thermal conductivity. The data shows a reduction in temperature swing over the year with increasing thermal conductivity. This trend can be expected and is similar to the behavior of closed-loop U-Tube heat exchangers. When extracting heat from the ground in the winter higher thermal conductivities result in the temperature back to heat pump being higher. Conversely, when rejecting heat into the ground in the summer, higher thermal conductivities result in the temperature back to heat pump being lower. Increasing thermal conductivity allows greater heat fluxes along the borehole wall for the same temperature rise. Hence higher thermal conductivities are advantageous.

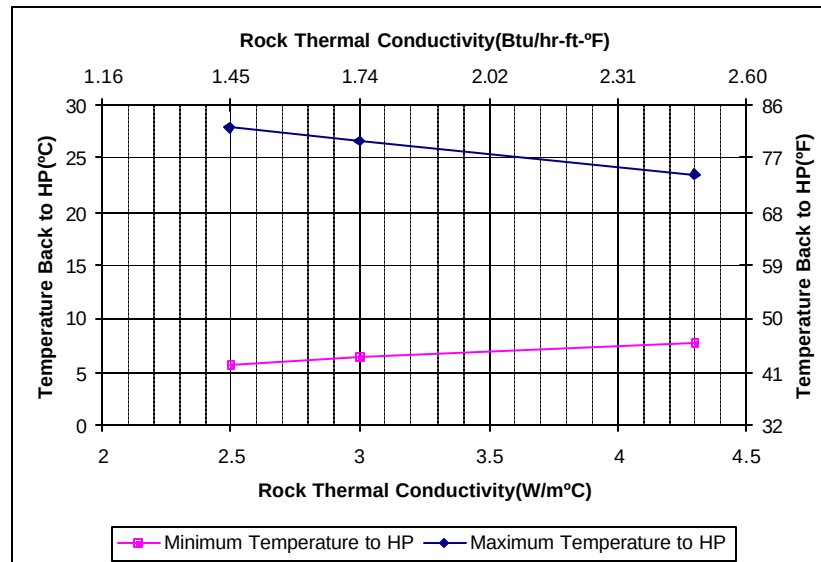


Figure 6.7: The effect of thermal conductivity of rock on the water temperature back to HP

6.2.2 Specific heat capacity

Figure 6.8 shows the variation of the minimum and maximum exiting fluid temperatures with rock specific heat capacity. When extracting heat from the ground in the winter higher specific heats result in the temperature back to heat pump being higher. Conversely, when rejecting heat into the ground in the summer, higher specific heats result in the temperature back to heat pump being lower. Higher specific heat capacity means the thermal capacity of the rock is larger, and under a given heat flux (load), the temperature change of the rock is smaller. The higher specific heat capacity leads to increase the damping of dynamic changes in the borehole temperatures.

6.2.3 Geothermal gradients

Figure 6.9 shows the variation of the minimum and maximum exiting fluid temperatures with rock thermal temperature gradient. Higher thermal gradients result in higher mean rock temperatures over the length of the borehole. This would be particularly true for deeper wells. The data shows that when heat is being extracted or heat rejected, the

higher natural geothermal gradients lead to the higher water temperatures back to heat pump. The performance of SCW would improve (in the winter) or degrade (in the summer). This is probably advantageous in most applications, in which the design considerations are based on heating conditions.

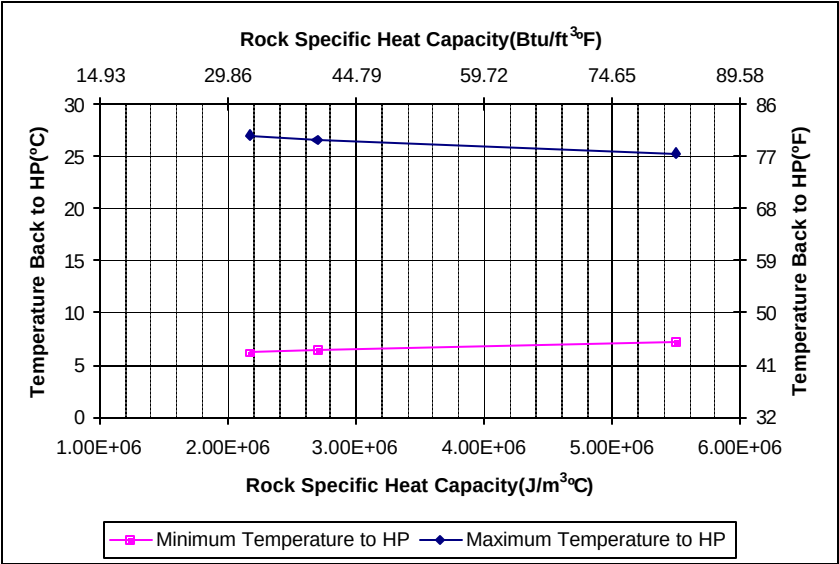


Figure 6.8: The effect of specific heat capacity of rock on the water temperature back to the HP.

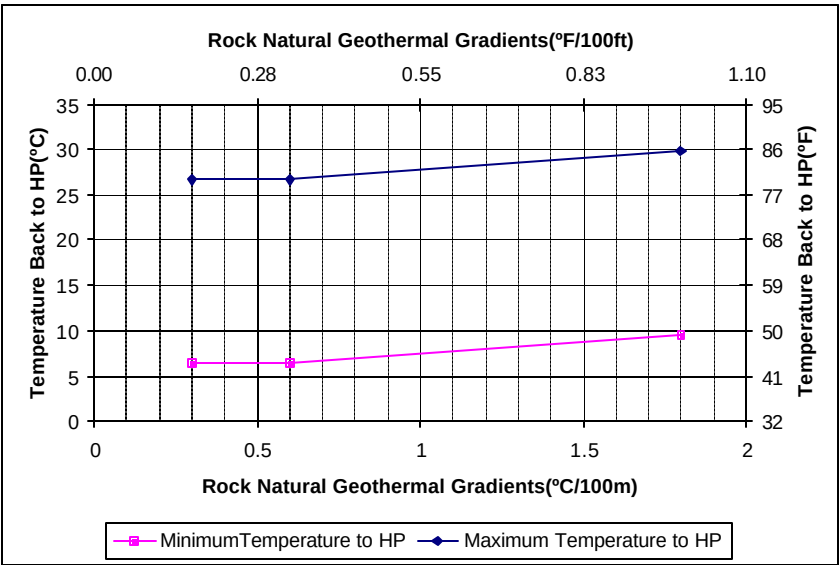


Figure 6.9: The effect of natural geothermal gradients of rock on the water temperature back to the HP.

6.2.4 Rock hydraulic properties

Figure 6.10a shows the variation of the minimum and maximum exiting fluid temperature with rock hydraulic conductivity. Moderate effect on the maximum and minimum exiting water temperature can be seen at higher hydraulic conductivity (case kh2, $[K_h=1.00E-04$ m/s]) and at the lower hydraulic conductivity (case kh3, $[K_h=1.00E-06$ m/s]). It could be expected that at higher hydraulic conductivities the resulting increased advective flow would lead to improved performance. However the results show that when hydraulic conductivity is increased, the maximum performance is found some way between the maximum and minimum values of this parameter. In order to investigate the effect of the hydraulic conductivity further, calculations were made for five cases using a two-week operation period.

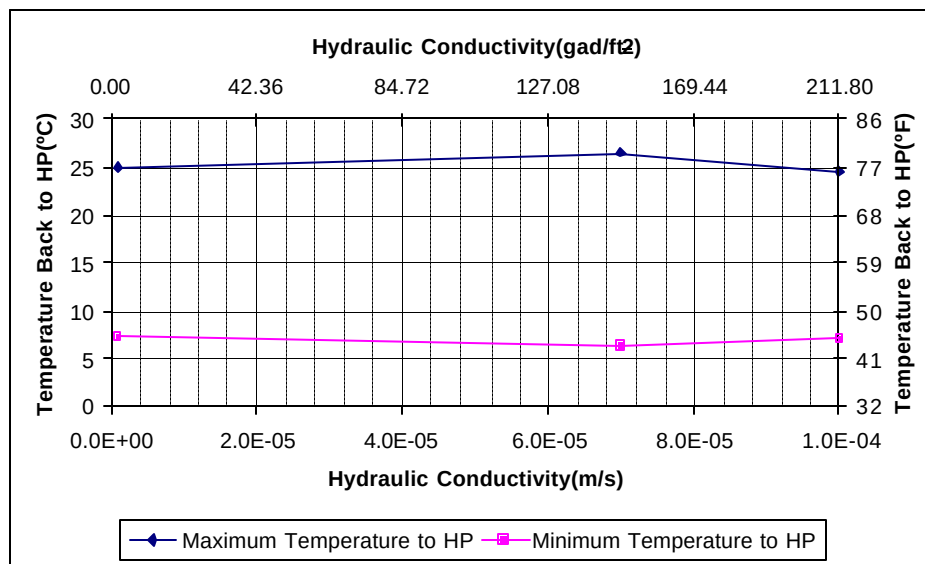


Figure 6.10a: The effect of hydraulic conductivity of rock on the water temperature back to HP

There are two modes of heat transfer along the borehole wall between fluid and rock: advective and convective heat transfer. As fluid flows down the borehole a boundary layer is formed at the borehole wall resulting in convective heat transfer. As the borehole wall is porous further heat transfer takes place by advection of fluid into and out of the rock. As the hydraulic conductivity increases the corresponding advective heat transfer increases. However, as the flow into and out of the rock increases the fluid flow vertically in the borehole reduces.

The heat transfer due to the two modes of heat transfer at the borehole wall has been calculated for each component and is shown in Fig. 6.10b. It can be seen that as hydraulic conductivity increases advective heat transfer increases. Convective heat transfer correspondingly decreases. As both these modes of heat transfer are of similar magnitudes there is a noticeable trade-off in heat flux as hydraulic conductivity is increased. Above in intersection of these curves (approximately $K_h = 2.0E-5$ m/s) advection heat transfer is dominant. Correspondingly, below this intersection convective

heat transfer is dominant. The total heat flux – due to both modes of heat transfer – therefore reaches a minimum near the intersection. This accounts for the fact that the exiting fluid temperatures calculated (Fig 10a) show a maximum between the minimum and maximum values of hydraulic conductivity. It should be noted that different borehole configuration (e.g. borehole diameter) would give different critical value of the intersection C and that it might still be desirable to have high hydraulic conductivity for other reasons.

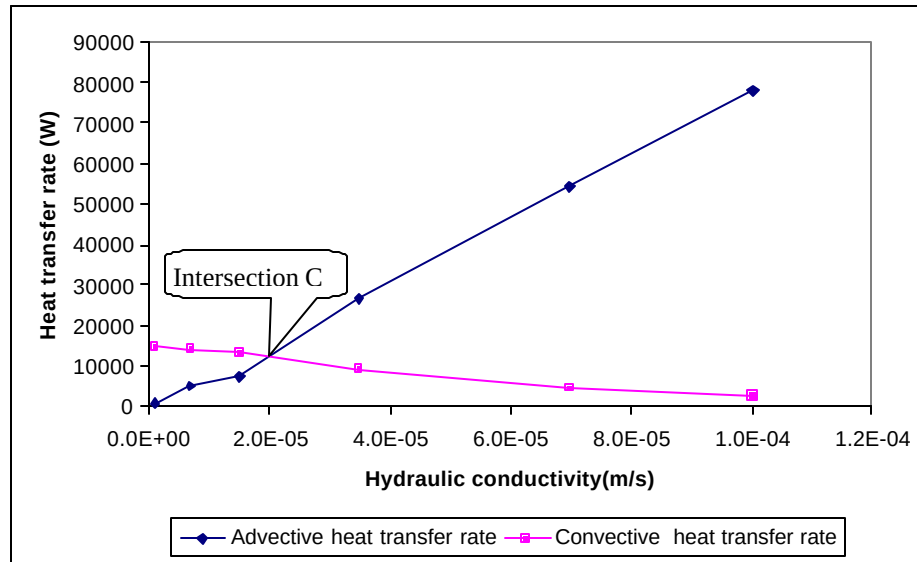


Figure 6.10b: Heat transfer rate along borehole wall in the different cases⁺

⁺ All the data in this Figure are generated by two-week (336hours) simulation with fixed water temperature (39.4°C [103°F]) into borehole. All the data are corresponding to the last time step (336th time step).

6.2.5 Borehole surface roughness

Figure 6.11 shows the variation of the minimum and maximum exiting fluid temperatures with borehole wall surface roughness. Increased surface roughness increases the borehole wall's surface area and promotes local turbulent flow at the wall of borehole, which should augment the heat transfer – resulting in a moderating effect on maximum and minimum exiting temperatures. This trend is seen in Figure 6.11, however, the effect does not seem to be significant compared to that associated with other design parameters.

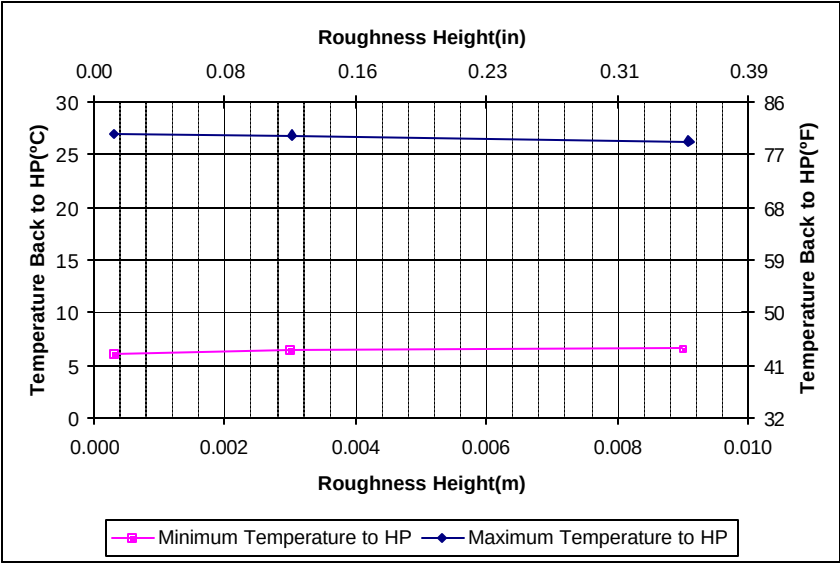


Figure 6.11: The effect of roughness height of borehole wall on the water temperature back to the HP.

6.2.6 Borehole diameter

Figure 6.12 shows the variation of the minimum and maximum exiting fluid temperatures with borehole diameter. In order to enhance the turbulent flow in the annular area in the borehole, it is desirable that the annular area should be smaller than the area inside the tubes. Figure 6.12 shows that there is only little difference between cases with different diameter of borehole

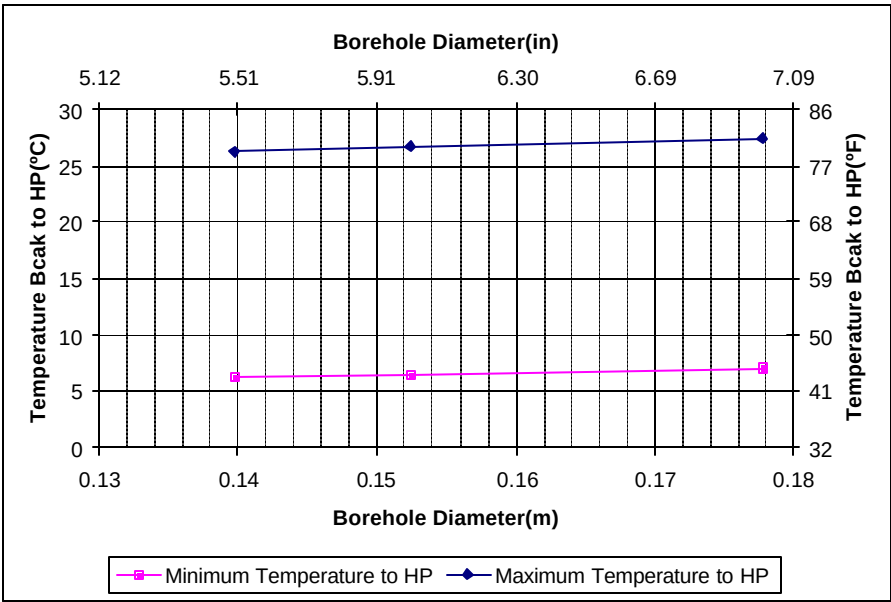


Figure 6.12: The effect of borehole diameter on the water temperature back to the HP.

6.2.7 Casing depth

The variation of the minimum and maximum exiting fluid temperatures with casing depth is shown in Figure 6.12. Increasing casing depth can be seen to increase maximum and decrease minimum exiting fluid temperatures. The heat exchanger performance is degraded with increasing casing depths. This might be expected as the casing restricts the ground-water flow around the well. Clearly, no ground-water can infiltrate into or out of the well over the depth of the casing. Overall Advective heat transfer will consequently be reduced. The effect however, is not as significant as might be expected. This effect might be more noticeable in rocks with higher hydraulic conductivities.

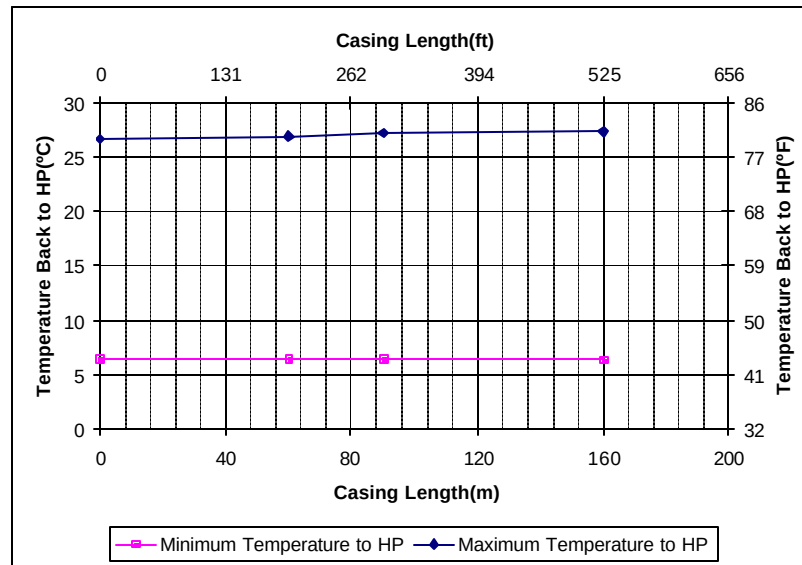


Figure 6.13: The effect of casing length on the water temperature back to the HP.

6.2.8 Dip tube insulation and diameter

Two cases were used to examine the effects of different levels of dip tube insulation (i.e. thermal conductivity). The variation of the minimum and maximum exiting fluid temperatures for these cases is shown in Figure 6.14. The variation of the minimum and maximum exiting fluid temperatures with dip tube diameter is shown in Figure 6.15.

The results for case d6 – with higher dip tube thermal conductivity – in Fig. 6.14, show greater maximum and lower minimum exiting fluid temperatures compared to the base case. As noted in the discussion of the well temperature distribution (Section 6.1), heat transfer between the fluid in the suction tube and the fluid surrounding the dip tube is detrimental. Consequently higher dip tube thermal conductivities can be expected to show poorer SCW performance. The effect shown in these cases however is not that great.

The dip tube diameter parameter was varied between 76 and 114mm (3-4.5in) in the parametric study. This changes the annular area noticeably when the borehole diameter is 156mm (6in). However, the results shown in Fig. 6.15 show that this parameter has had little effect on the SCW performance when varied in this range.

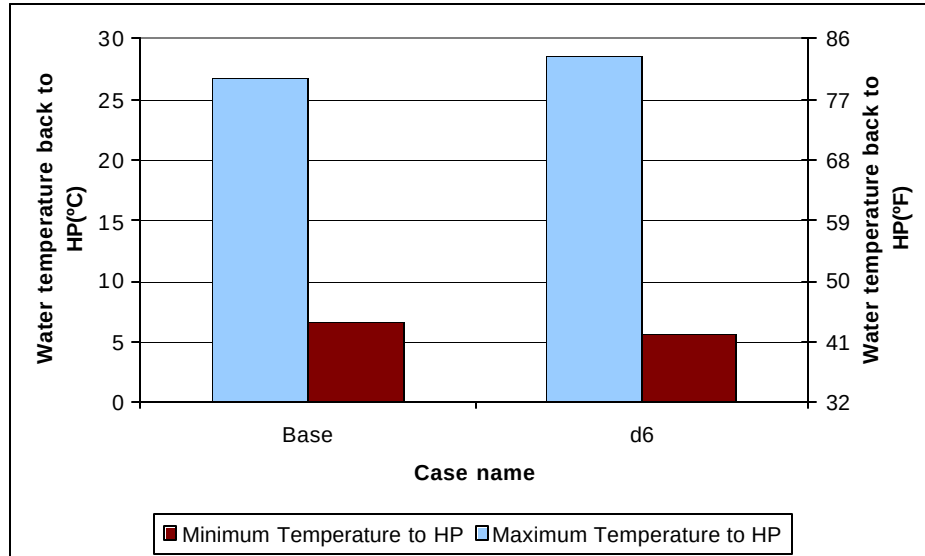


Figure 6.14: The effect of thermal insulation of the dip tube on the water temperature back to the HP.

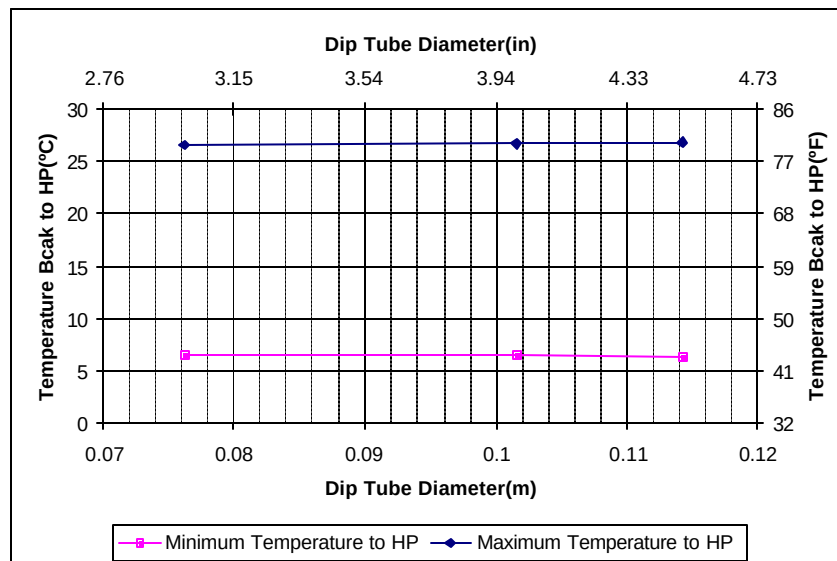


Figure 6.15: The effect of diameter of dip tube on the water temperature back to the HP.

6.2.9 Bleed rate

The bleed parameter calculations were made by making a two-year simulation, with no bleed in the first year, then introducing a constant bleed rate in the second year. The variation of the minimum and maximum exiting fluid temperatures with bleed rate is shown in Figure 6.16. The results show how significantly the minimum and maximum temperatures can be moderated by introduction of bleed. As the bleed rate is increased the minimum and maximum temperatures approach the far field temperature. This effect can be seen to be non-linear. This in itself might be expected (in the mathematical model the advection term of the energy equation makes it non-linear – without this term the equation is linear with constant coefficients). The most significant changes compared with the base case (zero bleed) occur in the range 0-5%. From this data it could be argued that there is little advantage in increasing the bleed rate beyond ten percent. There are diminishing returns with higher bleed rates as increased bleed results in higher pump energy consumption.

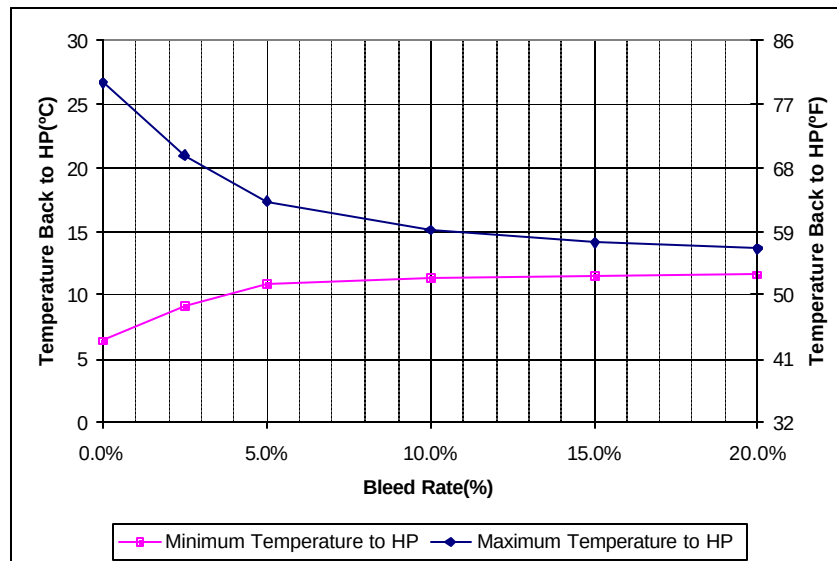


Figure 6.16: The effect of bleed rate on the water temperature back to the heatpump.

The effect of varying borehole depth at different bleed rates is discussed in section 6.2.15.

6.2.10 Borehole depth

The variation of the minimum and maximum exiting fluid temperatures with borehole depth is shown in Figure 6.17. Borehole depth was varied from 240-400m (787-1312ft) (with the loads kept the same) in the parametric study. 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 non-linear. This might be expected as, in addition to the load per unit depth changing, end effects become more significant at reduced depths. Also, as a temperature gradient is applied the mean ground temperature becomes lower with shorter depths.

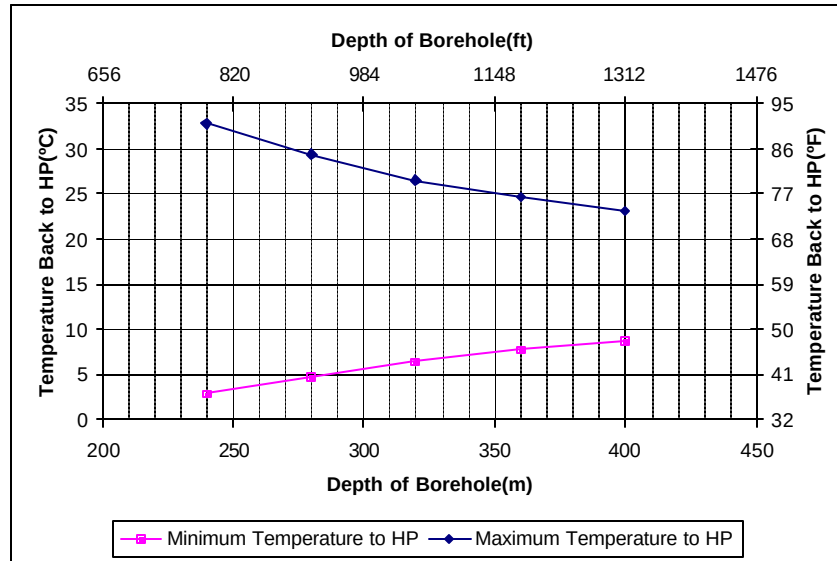


Figure 6.17: The effect of depth of borehole on the water temperature back to the HP.

The effect of varying borehole depth at different bleed rates is discussed in section 6.2.15.

6.2.11 Rock type

Although some of the previous cases deal with variations in individual rock thermal property variations (i.e. thermal conductivity or specific heat), three cases have been included where the hydraulic conductivity, thermal conductivity and porosity are all varied. The values of these parameters have been chosen to be representative of particular rock types. The base case has properties representative of karst limestone. The additional cases are representative of dolomite (case kt4), fractured igneous rock (case kt5) and sandstone (case Kh4).

The minimum and maximum SCW exiting water temperatures are compared in figure 6.18. In these cases the most significant variations are in thermal and hydraulic conductivity. 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.

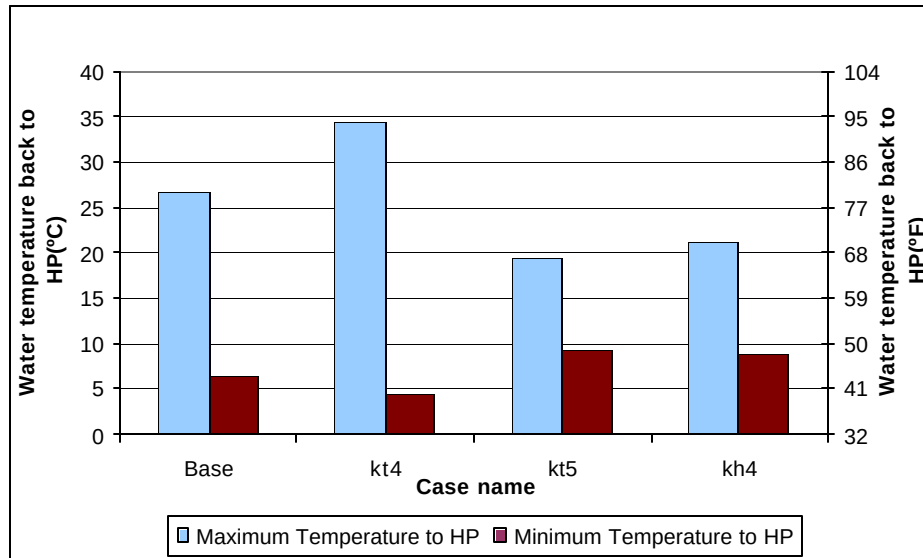


Figure 6.18: The effect of rock type on the water temperature back to the HP.

6.2.12 Bleed control strategy

The variation of the minimum exiting water temperature with different bleed control strategy is shown in Figure 6.19. Although the deadband control and temperature-difference control strategies were arranged to give bleed for the same number of hours, the temperature difference control gave a slightly higher minimum temperature. The minimum water temperature back to HP with no bleed was calculated to be 2.0 °C (35.6°F). This implies, in fact, that at this time water temperatures in the annulus of the well are below freezing point.

For the calculations where deadband and temperature-difference bleed control was modeled, the minimum water temperature back to the heatpump was increased to 5.4 °C (41.7°F) and 5.9°C (42.6°F) respectively. In these cases the minimum temperature in the borehole annulus was always above freezing. The result for the calculation with constant bleed is included in Fig. 6.19 for comparison. The minimum temperature in that case was 10.3°C (50.5°F). If the primary concern is to avoid freezing of the borehole intermittent bleed may suffice and constant bleed is probably unnecessary.

Although the total hours the pump ran was the same in controlled bleed cases, the hours when the pump ran were different. Some small difference in results could then be expected due to the dynamic nature of the system and changing loads. The results may show lower return temperatures for the temperature-difference control in other cases with different load profiles.

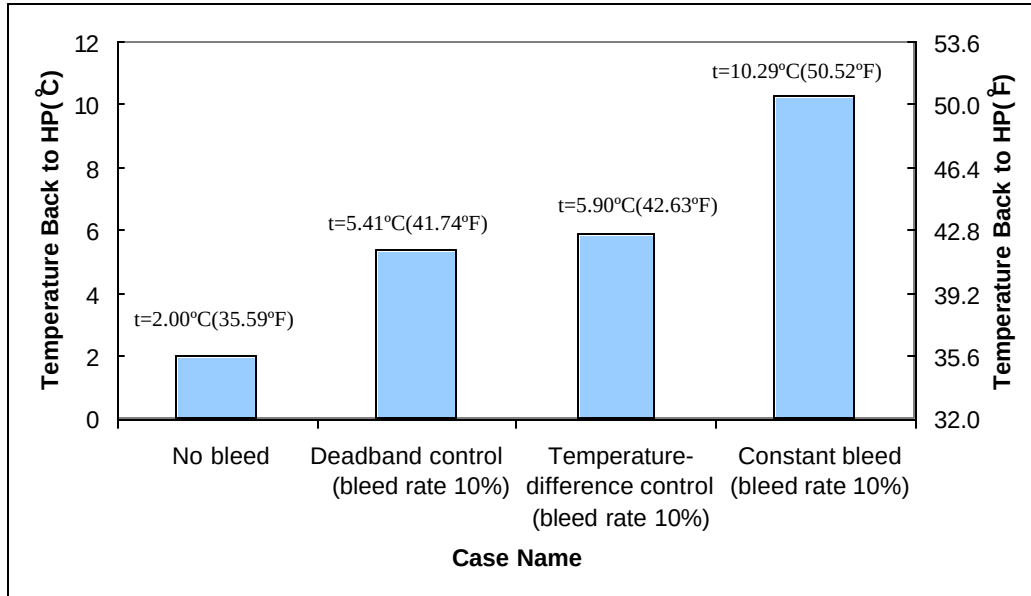


Figure 6.19: The effect of different bleed control strategy on the minimum water temperature back to HP in winter (January and February)

Figure 6.20 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. Figure 6.21 shows the relations between the temperature difference and the bleed period in temperature-difference bleed control case.

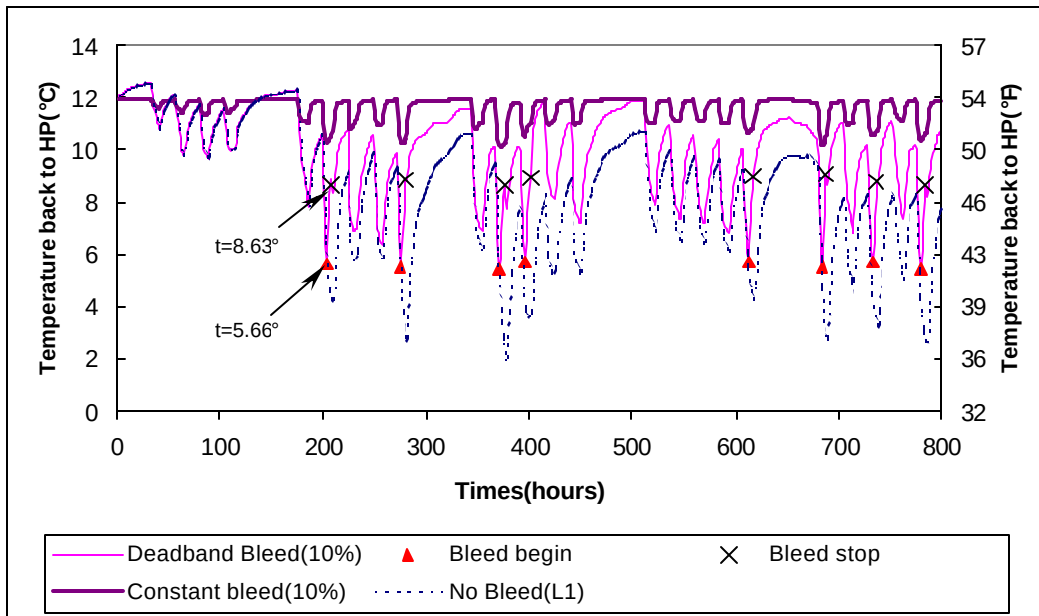


Figure 6.20: Comparison water temperature back to the heat pump between non-bleed case, constant bleed and deadband bleed control case.

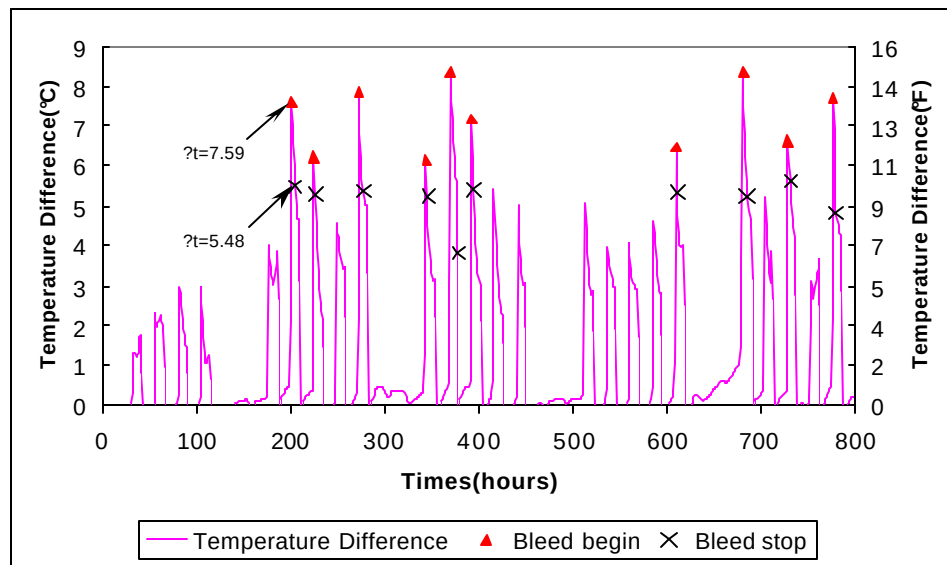


Figure 6.21: Entering-exiting fluid temperature difference during the heating season under temperature-difference bleed control showing the points at which bleed was activated.

6.2.13 Reversed flow configuration

Two cases including base case were used to examine the effects of reversed configuration. Water was drawn from the bottom of the borehole and discharged near the top in the base case, but was drawn from the top of the borehole in reversed case and discharged at the bottom. Figure 6.22 shows the variation of the minimum and maximum exiting water temperatures for these cases. The results suggest that reversing the configuration has a small effect on the SCW performance. As temperatures are shown to be higher in the base case, this would seem the logical configuration for heating-load dominated buildings (as is found in practice). Reversed flow may be beneficial in buildings that are more dominated by cooling loads. The heat transfer mechanisms can be expected to work in much the same way in both arrangements. Heat transfer between water in the dip tube and the surrounding water in the annulus of borehole works against the overall SCW capacity in both cases.

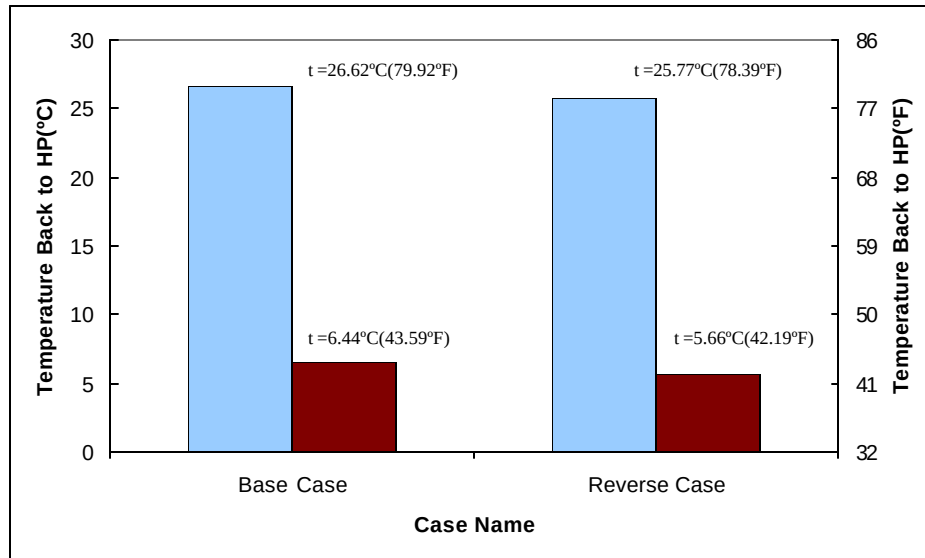


Figure 6.22: The effect of reversed configuration on the minimum and maximum water temperature back to HP

6.2.14 Impact of well bore diameter on storage capacity

The minimum and maximum exiting fluid temperatures in certain installations are thought to be particularly sensitive to the peak loads. In these cases it may be that performance may be improved as the volume of water in the system is increased. With higher system water volumes peaks in temperature should be damped by the increased thermal capacity. In standing column wells a large amount of water is contained in the borehole and this volume changes dramatically with borehole diameter.

To investigate this effect calculations were made for two weeks of the year (in January and July) using shorter time steps (hourly) and with borehole diameters of 150, 175 and 200mm (6, 7 and 8 in.) diameter. The resulting temperature profiles are shown in Fig 6.23 for the hours in January, and Fig. 6.24 for the hours in July. In both heating and cooling modes larger borehole diameter is shown to have a significant effect on damping the temperature swings and improving performance. At some times the minimum or maximum temperatures are shown to improve by as much as approximately 2°C (3.6°F).

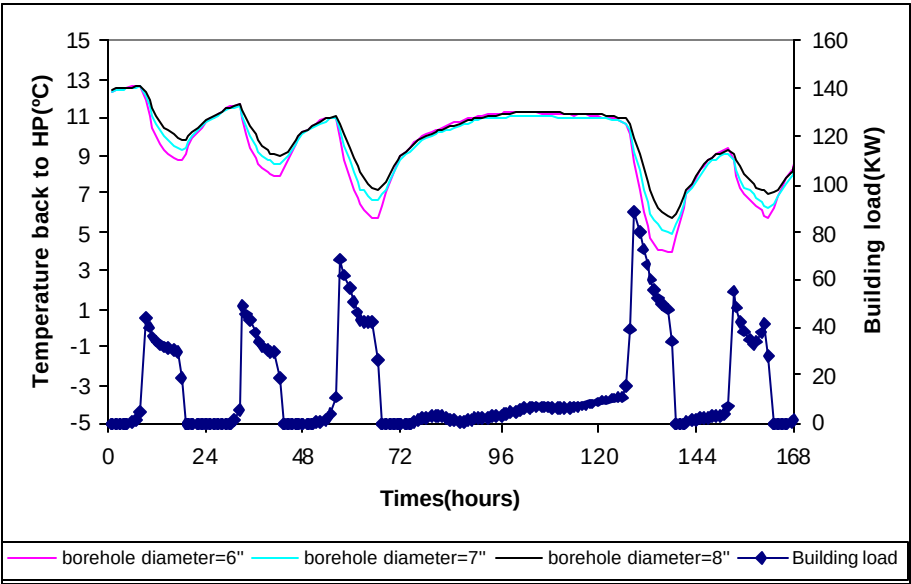


Figure 6.23: Simulation results for different borehole diameter in winter

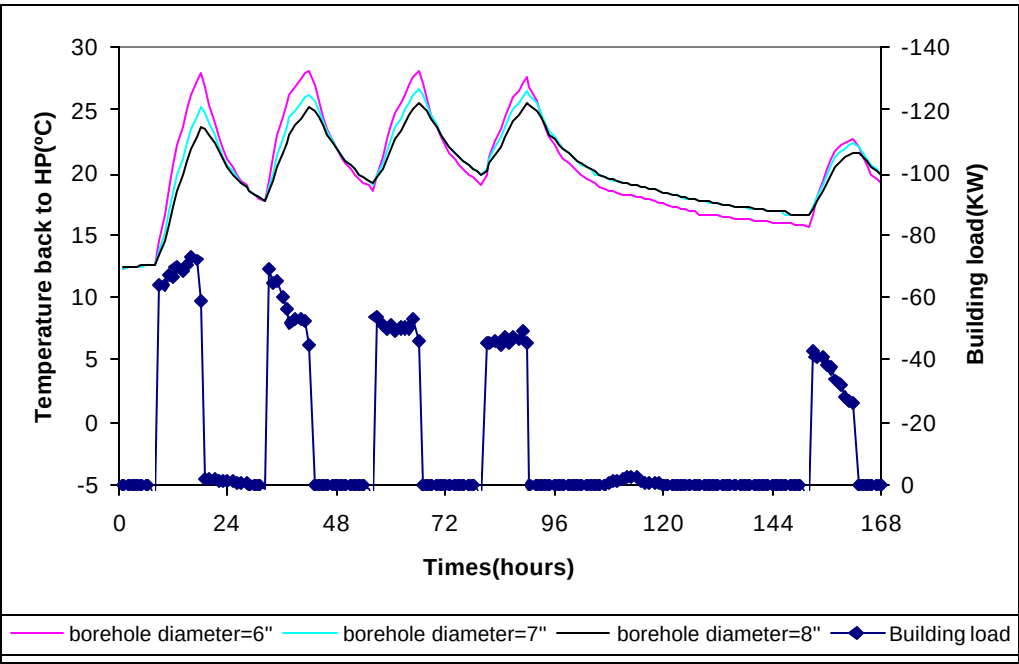


Figure 6.24: Simulation results for different borehole diameter in summer

6.2.15 Varied depth with different bleed rates

The simulation results show the exiting water temperature to be most sensitive to rock thermal conductivity, bleed rate and depth of borehole. Figure 6.25 shows the combined effect of depth of borehole and bleed rate on the water temperature back to the heat pump. In these cases borehole depth varied from 240-360m (787-1181 ft), and bleed rates were 0%, 5% and 10% with the loads kept the same.

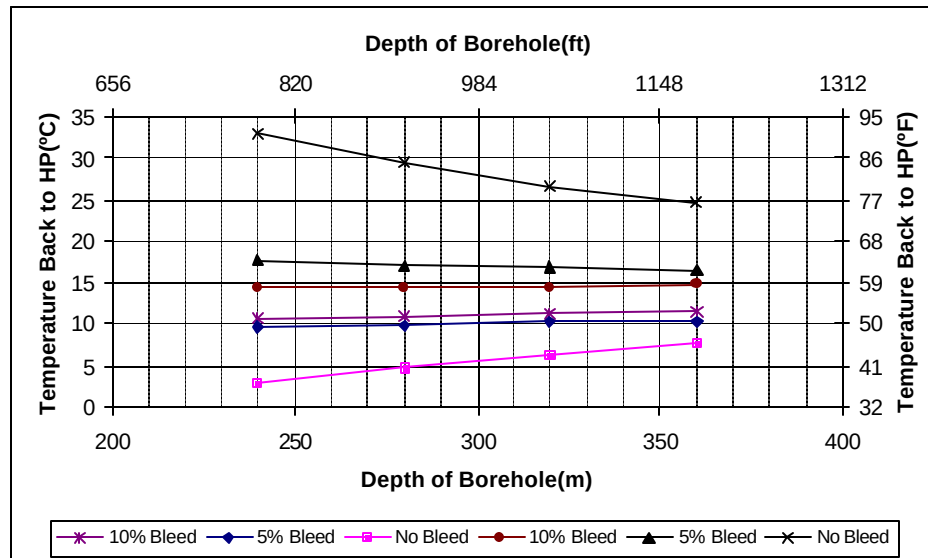


Figure 6.25: The combined effect of depth of borehole and bleed rate on the minimum and maximum water temperature back to HP

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 same exiting water temperatures. Higher bleed rates reduce the effect of depth on the SCW performance. For a given bleed rate, the effect of the depth of borehole can be seen to be a slightly non-linear in all cases. As noted in the discussion of the effect of the depth of borehole (Section 6.2.9), in addition to the load per unit depth changing, end effects become more significant at reduced depth.

6.2.16 System Energy Consumption and Costs

System energy consumption (heat pump + circulating pump) and associated costs have been calculated for each case using the method described in Section 5.3. The calculations results are presented for water table depths of 5m and 30m to show the effect of increased pumping power at lower water tables. The results are shown in Table 6.2 for a water table depth of 5m, and in Table 6.3 for a water table depth of 30m. The average annual power consumption has been expressed in terms of power consumption per unit of heating/cooling (kW/ton).

R&D Studies applied to SCW design

Results

Table 6.2
Energy calculation results (water table =5.0m)

Parameter Varied	Case name	Parameter Values	Power consumption per ton of load (kW/ton)	One year operating cost (\$)
Thermal conductivity		W/m°C (Btu/hr.ft.°F)		
	kt2	2.5 (1.44)	1.14	1500
	Base	3.0 (1.73)	1.13	1482
	kt3	4.3 (2.48)	1.09	1446
Natural geothermal gradients		°C/100m (°F/100ft)		
	n2	0.3 (0.17)	1.13	1482
	Base	0.6 (0.329)	1.13	1482
	n3	1.8 (0.99)	1.17	1519
Specific heat capacity		J/m³°C (Btu/ft³.°F)		
	s2	2.13E+06 (31.769)	1.13	1486
	Base	2.70E+06 (40.27)	1.13	1482
	s3	5.50E+06 (82.03)	1.11	1470
Borehole diameter		mm (in)		
	d2	139.8 (5.5)	1.14	1472
	Base	152.4 (6)	1.13	1482
	d3	177.8 (7)	1.13	1498
Bleed rate		Bleed rate (%)		
	Base	0	1.13	1482
	b4	2.5	1.05	1408
	b5	5.0	1.01	1368
	b1	10.0	0.975	1343
	b2	15.0	0.963	1334
	b3	20.0	0.957	1331
Casing depth		m (ft)		
	Base	0 (0)	1.13	1482
	c4	60 (197)	1.13	1487
	c3	90 (295)	1.13	1490
	c2	160 (525)	1.14	1493
Surface roughness		mm (in)		
	h2	0.3(0.01)	1.13	1488
	Base	1.5 (0.06)	1.13	1482
	h4	3.0 (0.12)	1.13	1484
	h3	9.0 (0.35)	1.12	1480

R&D Studies applied to SCW design

Results

Table 6.2 continued
Energy calculation results (water table =5.0m)

Parameter Varied	Case name	Parameter Values	Power consumption per ton of load (kW/ton)	One year operating cost (\$)
Hydraulic conductivity		m/s (gal/day/ft²)		
	kh3	1.00E-06 (2.118)	1.11	1472
	Base	7.00E-05 (148.23)	1.13	1482
	kh2	1.00E-04 (211.8)	1.10	1454
Dip tube diameter		mm (in)		
	d4	76.2 (3)	1.12	1485
	Base	101.6 (4)	1.13	1482
	d5	114.3 (4.5)	1.13	1484
	d6	101.6(4) (insulation different)	1.15	1503
Depth of borehole		m (ft)		
	L1	240 (787)	1.21	1569
	L2	280 (919)	1.16	1521
	Base	320 (1050)	1.13	1482
	L3	360 (1181)	1.10	1461
	L4	400 (1321)	1.08	1443
Different rock type		Rock type		
	Base	Karst limestone	1.13	1482
	kt4	Dolomite	1.24	1600
	kt5	Fractured igneous and metamorphic	1.07	1399
	kh4	Sandstone	1.07	1423
Bleed control		Bleed rate (%)		
	L1	0	1.21	1569
	L1_bt3	5.0(Dead-band)	1.19	1540
	L1_bt1	10.0(Dead-band)	1.20	1541
Reverse		Reverse		
	No reverse	Base	1.13	1482
	Reverse	Reverse	1.12	1469

Table 6.2 continued
Energy calculation results (water table =5.0m)

Parameter Varied	Case name	Parameter Values		Power consumption per ton of load (kW/ton)	One year operating cost (\$)
Depth of borehole and Bleed rate		m (ft)	Bleed rate(%)		
	L1_bleed(5)	240 (787)	5	1.01	1363
	L2_bleed(5)	280 (919)	5	1.00	1365
	b5(2)	320 (1050)	5	0.999	1364
	L3_bleed(5)	360 (1181)	5	0.995	1368
Depth of borehole and Bleed rate		m (ft)	Bleed rate(%)		
	L1_bleed(10)	240 (787)	10	0.966	1339
	L2_bleed(10)	280 (919)	10	0.968	1341
	b1(2)	320 (1050)	10	0.968	1341
	L3_bleed(10)	360 (1181)	10	0.971	1342
Bleed rate (one-year operation)		Bleed rate (%)			
	Base	0		1.13	1482
	b4(2)	2.5		1.05	1404
	b5(2)	5.0		0.999	1364
	b1(2)	10.0		0.968	1341
	b2(2)	15.0		0.959	1333
	b3(2)	20.0		0.954	1331

R&D Studies applied to SCW design

Results

Table 6.3
Energy calculation results (water table =30.0m)

Parameter Varied	Case name	Parameter Values	Power consumption per ton of load (kW/ton)	One year operating cost (\$)
Thermal conductivity		W/m°C (Btu/hr.ft.°F)		
	kt2	2.5 (1.44)	1.15	1521
	Base	3.0 (1.73)	1.13	1503
	kt3	4.3 (2.48)	1.09	1467
Natural geothermal gradients		°C/100m (°F/100ft)		
	n2	0.3 (0.17)	1.13	1503
	Base	0.6 (0.329)	1.13	1503
	n3	1.8 (0.99)	1.17	1540
Specific heat capacity		J/m³°C (Btu/ft³.°F)		
	s2	2.13E+06 (31.769)	1.14	1507
	Base	2.70E+06 (40.27)	1.13	1503
	s3	5.50E+06 (82.03)	1.11	1491
Borehole diameter		mm (in)		
	d2	139.8 (5.5)	1.14	1493
	Base	152.4 (6)	1.13	1503
	d3	177.8 (7)	1.14	1519
Bleed rate		Bleed rate (%)		
	Base	0	1.13	1503
	b4	2.5	1.05	1439
	b5	5.0	1.01	1409
	b1	10.0	0.981	1402
	b2	15.0	0.972	1413
	b3	20.0	0.968	1428
Casing depth		m (ft)		
	Base	0 (0)	1.13	1503
	c4	60 (197)	1.13	1508
	c3	90 (295)	1.14	1511
	c2	160 (525)	1.14	1514
Surface roughness		mm (in)		
	h2	0.3(0.01)	1.13	1509
	Base	1.5 (0.06)	1.13	1503
	h4	3.0 (0.12)	1.13	1505
	h3	9.0 (0.35)	1.13	1501

R&D Studies applied to SCW design

Results

Table 6.3 continued
Energy calculation results (water table =30.0m)

Parameter Varied	Case name	Parameter Values	Power consumption per ton of load (kW/ton)	One year operating cost (\$)
Hydraulic conductivity		m/s (gal/day/ft²)		
	kh3	1.00E-06 (2.118)	1.11	1493
	Base	7.00E-05 (148.23)	1.13	1503
	kh2	1.00E-04 (211.8)	1.10	1475
Dip tube diameter		mm (in)		
	d4	76.2 (3)	1.13	1506
	Base	101.6 (4)	1.13	1503
	d5	114.3 (4.5)	1.13	1505
	d6	101.6(4) (insulation different)	1.15	1524
Depth of borehole		m (ft)		
	L1	240 (787)	1.21	1591
	L2	280 (919)	1.17	1542
	Base	320 (1050)	1.13	1503
	L3	360 (1181)	1.10	1483
	L4	400 (1321)	1.08	1463
Different rock type		Rock type		
	Base	Karst limestone	1.13	1503
	kt4	Dolomite	1.24	1622
	kt5	Fractured igneous and metamorphic	1.07	1421
	kh4	Sandstone	1.07	1444
Bleed control		Bleed rate (%)		
	L1	0	1.21	1591
	L1_bt3	5.0(Dead-band)	1.19	1563
	L1_bt1	10.0(Dead-band)	1.20	1564
Reverse		Reverse		
	No reverse	Base	1.13	1503
	Reverse	Reverse	1.15	1505

Table 6.3 continued
Energy calculation results (water table =30.0m)

Parameter Varied	Case name	Parameter Values		Power consumption per ton of load (kW/ton)	One year operating cost (\$)
Depth of borehole and Bleed rate		m (ft)	Bleed rate(%)		
	L1_bleed(5)	240 (787)	5	1.02	1404
	L2_bleed(5)	280 (919)	5	1.01	1405
	b5(2)	320 (1050)	5	1.00	1404
	L3_bleed(5)	360 (1181)	5	0.999	1408
Depth of borehole and Bleed rate		m (ft)	Bleed rate(%)		
	L1_bleed(10)	240 (787)	10	0.973	1399
	L2_bleed(10)	280 (919)	10	0.974	1400
	b1(2)	320 (1050)	10	0.975	1399
	L3_bleed(10)	360 (1181)	10	0.978	1402
Bleed rate (one-year operation)		Bleed rate (%)			
	Base	0		1.13	1503
	b4(2)	2.5		1.05	1435
	b5(2)	5.0		1.00	1404
	b1(2)	10.0		0.975	1399
	b2(2)	15.0		0.967	1412
	b3(2)	20.0		0.964	1428

The annual energy costs for water table depth of 5m and 30m are shown in Figures 6.26 and 6.28 respectively. These figures show the contribution to the total cost of the pump power consumption relative to the heat pump power consumption. The energy efficiency — expressed as power consumption per unit of heat transfer — is shown in bar chart form in Figure 6.27 and 6.29 for water table depths of 5m and 30m respectively.

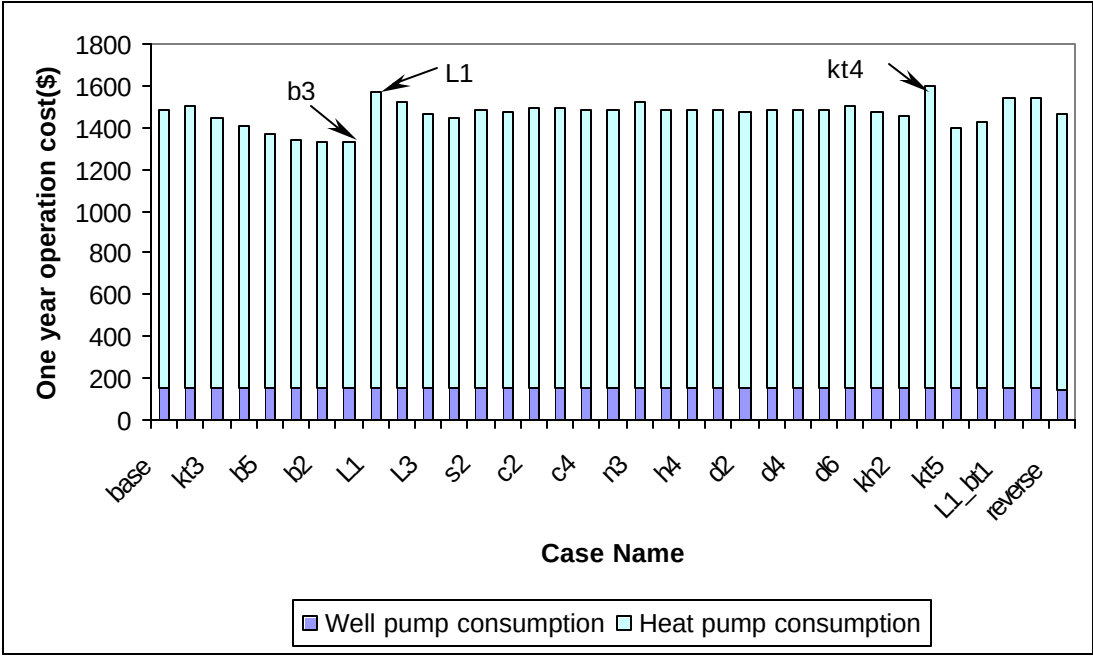


Figure 6.26 Annual energy costs showing the contribution of the well pump and heat pump (water table=5.0m).

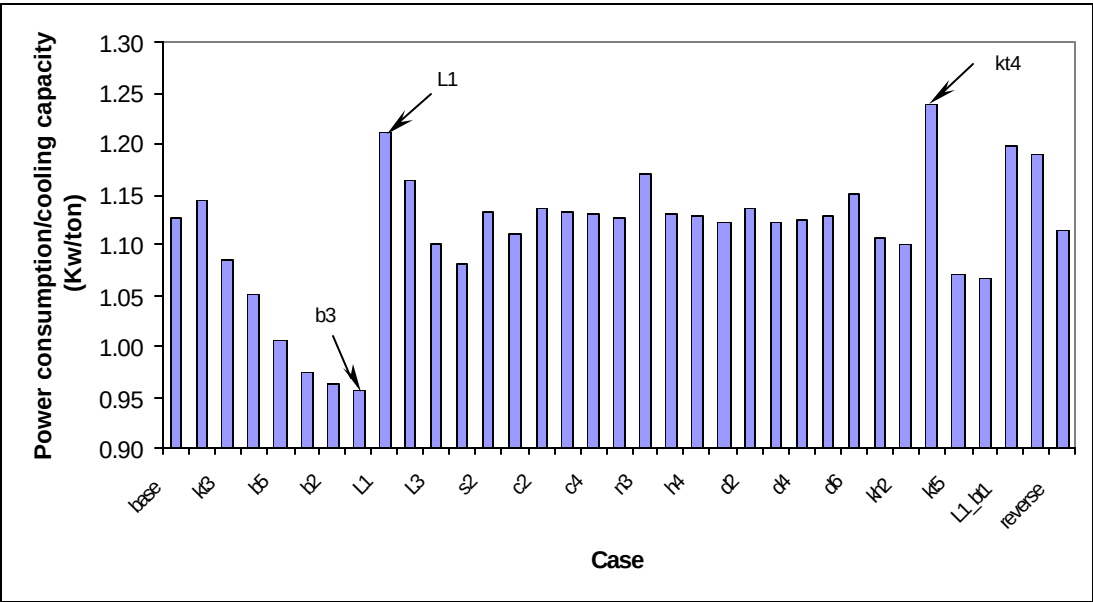


Figure 6.27 The ratio of power consumption to heat transfer capacity (water table = 5m).

The same trends are shown whether the energy cost or normalized power consumption is considered. When the water table is at a depth of 5m the pump energy costs remain nearly constant whether there is bleed or not (Fig. 6.26). The lowest costs for all cases are where:

- The borehole is longest
- The thermal conductivity is highest
- The bleed rate is highest

The poorest results are for the cases with short borehole length and lowest thermal conductivity (cases L1 and Kt4). In all cases with 5m water table depth energy costs are lower where the minimum and maximum temperatures are improved (i.e. closer to the load temperature) and the efficiency of the heat pump is consequently improved. At this depth of water table the higher cost of pump energy consumption at higher rates of bleed is outweighed by reduced heat pump energy costs. Similarly, there appears 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).

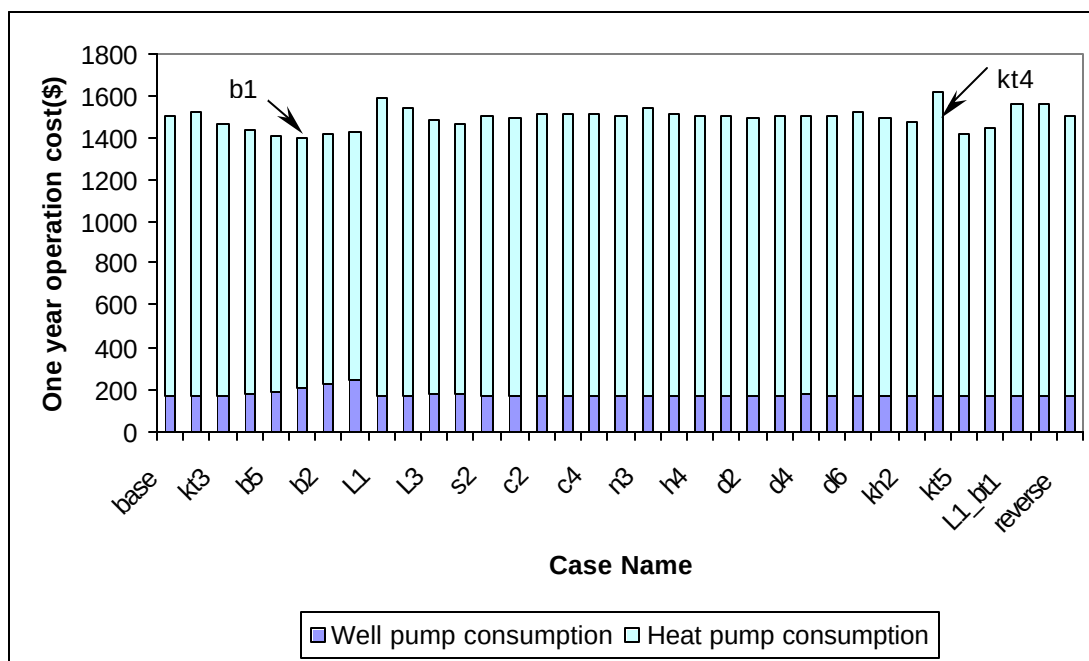


Figure 6.28 Annual energy costs showing the contribution of the well pump and heat pump (water table = 30m).

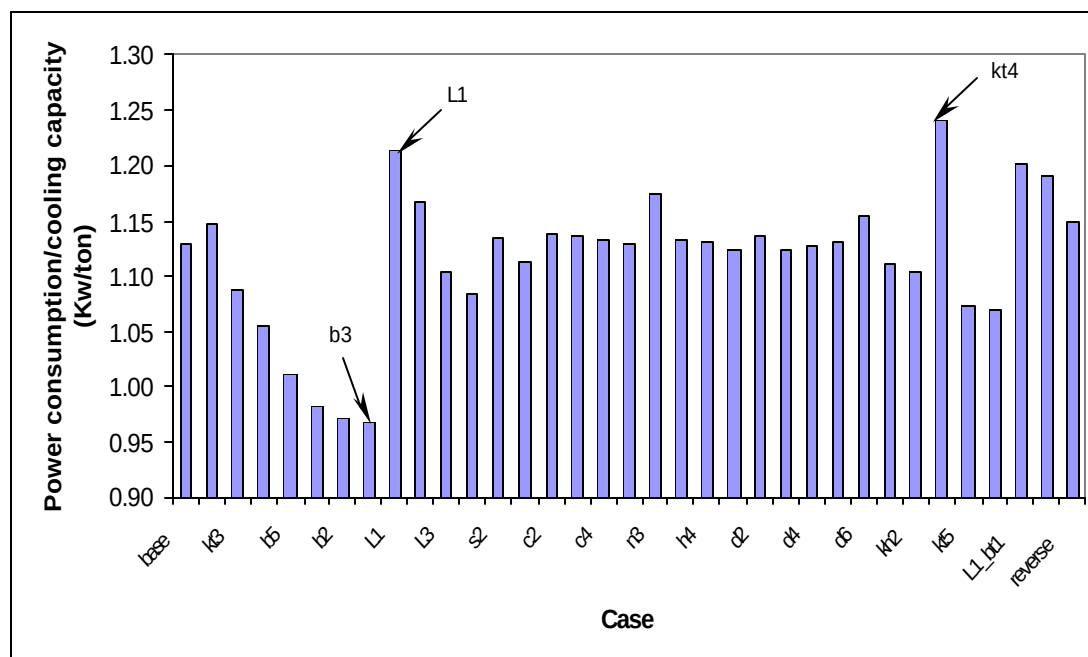


Figure 6.29 The ratio of power consumption to heat transfer capacity (water table = 5m).

For water table depth of 30m, again, the same trends are shown whether the energy cost or normalized power consumption is considered. When the water table is at a depth of 30m the pump energy costs are very similar to the 5m water table depth cases where there is no bleed (some additional pipe pressure drop is introduced). However, where there is bleed the pump energy consumption becomes more significant and increases dramatically at higher rates of bleed (Fig 6.28). The lowest costs for are where:

- The borehole is longest
- The thermal conductivity is highest

Again, the poorest results are for the cases with short borehole length and lowest thermal conductivity (cases L1 and Kt4). In all cases with 30m water table depth the heat pump component of the energy costs are lower where the minimum and maximum temperatures are improved and the efficiency of the heat pump is consequently improved. At lower rates of constant bleed system energy consumption can be improved in a similar manner to the cases with 5m water table depth. However, at this depth of water table and higher rates of bleed (> 10%) the higher cost of pump energy consumption starts to outweigh the benefit of improved heat pump efficiency. This can be seen in Fig. 6.30 where the results for both water table depths are compared side-by-side. Again, there appears 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).

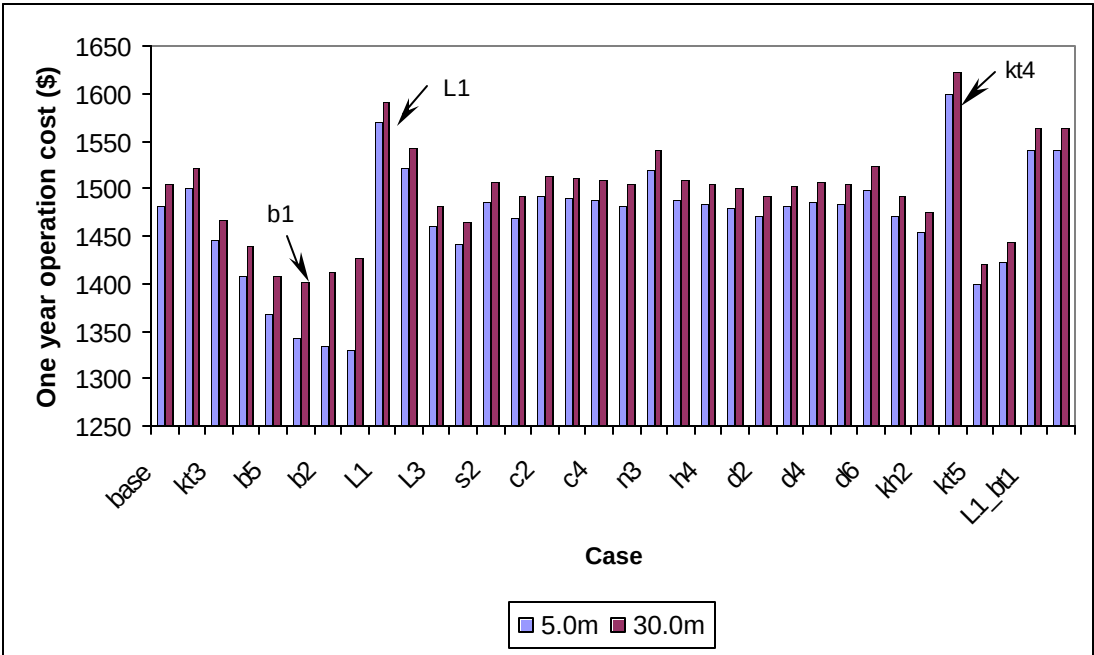


Figure 6.30 Comparison of annual energy costs for water table depths of 5m and 30m.

7.0 Conclusions

This report discusses the work of the ASHRAE research project 'R&D studies applied to standing column well design (1119-RP)'. The work has consisted of three major elements:

1. Survey and characterization of standing column well technology. This has included,
 - Survey and characterization of existing standing column well technology and installation practice
 - Collection and data from existing well installations
 - Characterization of geological and hydrological conditions in regions where standing column wells have been applied.
2. Development of a detailed model of a standing column well and surrounding geological formation.
3. A Study of the effect of the effects of and significance of standing column well design parameters. This has entailed using the model to calculate annual fluid temperatures driven by characteristic building loads.

Data from 34 wells at 21 locations have been collected and are believed to be representative of current installation practice and geographical distribution. These installations all have heating dominated loads. Heat extraction has accordingly been the main focus of these well and system designs. Bleeding of the well to induce flow of ground-water at more moderate temperatures into the well, is a key feature of the well and system designs. Three sites have been identified where detailed data is available.

Construction differences existing in the reported standing column wells relate in part to the depth of the well rather than any other influencing parameter. Shallower wells (i.e. depths less than 150m [500 ft.]) tend to be dominated by placement of the pump near the bottom of the well with the return located near the top. Deeper wells (depth greater than 150m [500 ft.]) mostly use dip tubes (Porter Shroud) constructed of 100mm (4 in.) diameter PVC pipe to the bottom of the well. The pump and return pipe end are located near the top of the well taking into account draw-down depths at bleed flow rates of from 5% to 25% of total heat pump flow depending on the application.

The location and hydraulic properties of the different 'ground-water regions' of North America have been presented. The regions where standing column well installations have been identified are all in the Northeast of North America. These are the (i) Northeastern Appalachians, (ii) Appalachian Plateaus and Valley and Ridge and, (iii) Piedmont and Blue Ridge regions. Each of these regions has igneous or metamorphic rock where relatively high well capacities and good water quality is available.

Previous models of standing column wells have made a number of assumptions about the heat transfer between the different components of the well. They have all treated in ground-water flow in the surrounding rock in a very simplified manner. The numerical model developed in this work is composed of two parts: a nodal model of the borehole components and a finite volume model of the ground-water flow and heat transfer in the surrounding rock. The model allows the explicit treatment of the advective heat transfer induced by the ground-water flow. This is of particular importance for the realistic treatment of bleed operation. Results in the form of ground-water flow distribution and well/rock temperature distribution are presented.

The numerical model has been employed in a parametric study of standing column well performance. A base case design was developed with parameter 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 highly intensive computational nature of the calculations (six computers were employed continuously over a 24 week period) only a limited number of cases could be considered and 6 hourly time steps were required.

The well performance has been characterized by minimum and maximum exiting fluid temperature and equivalent design borehole length. The performance was found to be most sensitive to the following parameters:

- Bleed rate
- Borehole length
- Rock thermal conductivity
- Hydraulic conductivity

A number of other parameters affect the convective heat transfer in the borehole but in themselves have only a secondary effect of the well performance:

- Borehole diameter
- Dip tube thermal conductivity
- Borehole wall roughness
- Fluid flow direction
- Ground thermal gradient
- Borehole casing depth

Sensitivity to ground thermal conductivity and borehole length can be expected from consideration of conductive heat transfer around the borehole. Bleed is strongly related to rock hydraulic conductivity i.e. high bleed rates are only feasible in rocks with high hydraulic conductivity. The combination of thermal conductivity and hydraulic conductivity is dependent on the rock type. Calculations using shorter time steps and increased borehole diameter have shown that performance is improved by virtue of the increased system volume damping minimum and maximum temperatures at peak loads. Performance varies with bleed rate in a highly nonlinear manner and a number of interesting characteristics have been identified.

- Performance can be improved dramatically by introducing bleed. However, at higher bleed rates (greater than 10% in this study) there is

little further gain in performance. (In certain installations, low borehole temperatures in peak heating conditions may still require bleed rates higher than 10%).

- With increasing bleed rate sensitivity to borehole length decreases. This is thought to be because at shorter borehole lengths ground-water flow velocity would theoretically increase – increasing the significance of the advective heat transfer – for the same bleed flow rate. In practice it may not be possible to maintain higher bleed flows at shorter borehole depths as the flow is limited by the hydrological conditions i.e. well flow capacity.
- As hydraulic conductivity increases there is a trade-off between convective and advective heat transfer at the borehole wall – increasing advection through the wall reduces convection along the wall. This means that very high hydraulic conductivities do not necessarily result in better performance than moderate values.

Annual energy consumption has been estimated for each case. Results show that poorest energy performance occurs in cases with the least favorable thermal and hydraulic conductivities. As may be expected, energy performance is not sensitive to the parameters that have already been noted to have little effect on standing column well thermal performance. 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).

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 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 higher bleed rates (calculations were made with bleed rates up to 20%) can significantly improve overall energy performance and can enable the borehole length to be reduced significantly. In practice however, there maybe a number of limitations on the amount of bleed that can be achieved, such as, limited well pumping capacity and practical difficulties in disposing of the bleed water.

Following this project, what remains to be done? There are two fundamental areas of investigation necessary to provide design methodologies and tools for designers. First,

R&D Studies applied to SCW design

Conclusions

some experimental validation of the detailed simulation tool developed for this project needs to be done. Second, once the detailed simulation tool has been validated, it may be used to investigate various procedures for simplified simulations.

Such simulations might be as simple as using the line source analysis with an “enhanced” thermal conductivity. If so, the detailed simulation procedure could be used to determine an appropriate method for modifying the thermal conductivity. More sophisticated, but still much faster, simulations which combine a line source with water storage in the borehole and where bleed is treated as some combination of groundwater flowing directly to the borehole and an enhanced thermal conductivity may also be imagined. Finally, a numerical model might be used if some pre-computed groundwater flows were used whenever bleed occurred. A variety of simple simulation models could be compared to detailed simulation results to identify the best procedure.

Once a simplified simulation tool has been developed, it will also be desirable to develop more thorough design guidelines. These may include recommended in situ tests, e.g. thermal conductivity and well draw-down tests; recommended design details, e.g. system configuration and material specifications; acceptable water quality, etc.

References

- ASHRAE 2001, ASHRAE Handbook of Fundamentals. American Society of Heating, Refrigerating and Air- Conditioning Engineers, Inc., Atlanta, GA.
- Bhatii, M.S. and Shah, R.H. 1987. Turbulent and transition flow convective heat transfer in ducts. *Handbook of single-phase convective heat transfer*. New York: John Wiley & Sons.
- 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., Klimkowki, H., and Oliver, J. 1983. Earth source heat exchanger for heat pumps. *Transactions of ASAE*. 26 :1818-1822.
- Chen,N.H.1979. An explicit equation for friction factor on pipe. *Industrial and Engineering Chemistry Fundamentals*. Vol 18, pp296-297.
- Chen, C. & Jiao, J.J. 1999 Numerical simulation of pumping tests in multiplayer wells with non-Dacican flow in the well bore. *Groundwater*. 37(3):465-474.
- Chiasson, A., Rees, S.J. and Spitler, J.D. 2000. A preliminary assessment of the effects of ground-water flow on closed-loop ground-source heat pump systems. *ASHRAE Transactions*. 106(1): 380-393
- Churchill, S. W. & Chu, H. S. 1975. Correction equations for laminar and turbulent free convection from a vertical plate. *International journal of heat and mass transfer*, 18: 1323-1329.
- Colebrook, C. F. 1939. Turbulent flow in pipes, with particular reference to the transition region between the smooth and rough pipe laws. *Institution of Civil Engineers*. pp133 -156.
- Domenico, P.A. and F. W. Schwartz. 1990. *Physical and Chemical Hydrogeology*. New York, Chicester, Brisbane, Toronto, Singapore: John Wiley & Sons.
- Driscoll, F. G. 1986. *Groundwater and Wells*. St. Paul Minnesota: Johnson Filtration Systems, Inc.
- Ferziger J.H. and M. Peric, 1996. *Computational Methods for Fluid Dynamics*. Berlin: Springer-Verlag. pp. 364.
- Freeze, R. A. and J. A. Cherry. 1979. *Groundwater*. Englewood Cliffs, New Jersey: Prentice Hall, Inc.

- Heath, R.C. 1984. *Ground Water Regions of the United States*. United States Geological Survey Water-Supply Paper 2242, 1984, 78 p.
- Heath, R.C. 1988. Hydrogeologic Settings of Regions (Chapter 3). In: *The Geology of North America, Vol. O-2, Hydrogeology*. Boulder, Colorado: The Geological Society of America, Inc., Edited by Back, W.B., J.S. Rosenshein, and P.R. Seaber.
- Hellstrom, G. 1991. *Ground Heat Storage. Thermal Analyses of Duct Storage Systems*. Lund, Sweden: University of Lund, Department of Mathematical Physics.
- Hopkirk R. J and Burkart R. 1990. Earth-coupled heat pumps. Heat pumps: solving energy and environmental challenges. *Proceedings of the 3rd International Energy Agency Heat Pump Conference*. Tokyo, Japan. pp411-421.
- LeGrand, H.E. 1988. Piedmont and Blue Ridge, Region 21 (Chapter 24). In: *The Geology of North America, Vol. O-2, Hydrogeology*. Boulder, Colorado: The Geological Society of America, Inc., Edited by Back, W.B., J.S. Rosenshein, and P.R. Seaber.
- Logan, J. 2001. Personal communication.
- Meinzer, O.E. 1923. *The Occurrence of Groundwater in the United States, with a Discussion of Principles*. United States Geological Survey Water-Supply Paper 489, 1923, 321 p.
- Mikler, V. 1993. *A Theoretical and Experimental Study of the "Energy Well" Performance*. Masters Thesis, The Pennsylvania State University.
- Norris, R. H. 1971. Some simple approximate heat transfer correlations for turbulent flow in ducts with rough faces. *Augmentation of convective heat and mass transfer, ASME*. pp16-26.
- Oliver, J., and Braud, H. 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. 1995. Design, use & example of standing column wells. *IGSPHA technical meeting*. May 15-17, 1995.
- Orio, C. D. 1999. Geothermal heat pump applications industrial /commercial. *Energy engineering*. 96(3): 58-66.

- Patankar, S.V. 1980. *Numerical Heat Transfer and Fluid Flow*. Hemisphere, Washington. pp. 197.
- Rafferty, K.D. 1998. Well-pumping issues in commercial groundwater heat pump systems. *ASHRAE Transactions*. 104(1B): 927-931.
- Randall, A.D., R.M. Francis, M.H. Frimpter, and J.M. Emery. 1988. Region 19, Northeastern Appalachians (Chapter 22). In: *The Geology of North America, Vol. O-2, Hydrogeology*. Boulder, Colorado: The Geological Society of America, Inc., Edited by Back, W.B., J.S. Rosenshein, and P.R. Seaber.
- Sachs, H. M and Dinse, D.R. 2000. Geology and the ground heat exchanger: what engineers need to know. *ASHRAE Transactions*. 106(2):421-433
- Stone, H.L. 1968. Iterative Solution of Implicit Approximations of Multidimensional Partial Differential Equations. *SIAM Journal of Numerical Analysis*. Vol.5, No.3, pp 530-558.
- Tan, C. and Kush, E. 1986. Semi-closed loop standing column well groundwater source heat pump. *GHPC website* www.geoexchange.org R&D project profile No.3.
- Techo, R. Tickner, R. R. & James, R.E. 1965. An accurate equation for the computation of the friction factor for smooth pipes from the Reynolds-number. *Journal of applied mechanics*. 32: 443.
- U.S. Geological Survey. 1995. *Ground Water Atlas of the United States, Segment 12*. Hydrologic Investigations Atlas 730-M, Reston, Virginia, 28 p.
- U.S. Geological Survey. 1997. *Ground Water Atlas of the United States, Segment 11*. Hydrologic Investigations Atlas 730-L, Reston, Virginia, 24 p.
- Van der Vorst, H.A., 1981. Iterative Solution methods for Certain Sparse Linear Systems with a no-symmetric Matrix arising from PDE-problems. *Journal of Computational Physics*, 44:1-19.
- Yuill, G. K., and Mikler, V. 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.

Appendix A: Questionnaire Sent to SCW Installers

XYZ Corp
J. Smith, Chief Engineer
Anycity, NY 22111

December 13, 1999

Dear Sir:

The Geo-Exchange heating/cooling industry uses a variety of methods to exchange heat with the ground. Furthermore, considerable research efforts have been spent on the improvement and understanding of earth coupled and ground water source systems in recent decades but there have been no similar efforts made for Standing Column Well systems. To promote the use of this technology a formal study of relevant factors has been initiated by the American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE).

We would like to elicit your help and contribution to ASHRAE technical data on the use and engineering of standing column wells as they apply to Geo-Exchange heating and cooling systems. A standing column well is defined by the characteristic of supplying well water to GeoExchange heat pumps and returning the water to the same well so that the sides of the well act as heat exchange surface between the well water and the ground (see attached figure).

ASHRAE's research project is under the direction of Oklahoma State's Dr. Jeffrey Spitler and is designed to create a solid base of technical reference material suitable for publication in the 'ASHRAE Handbook' to guide, educate and promote this energy efficient, clean heat source for the new millennium. We are collaborating with Dr. Spitler to survey existing well construction and performance data using Water & Energy System's extensive background in this technology for Geo-Exchange Heat Pumps.

This quest for exiting experience with standing column wells will form a vital link between theory and best industry practices. Your taking a few minutes to fill out the attached questionnaire for each standing column well you have designed/installed will assist in determining the future focus and emphasis with respect to research into various influences on well performance.

We intend to share the research results with all survey participants.

Yours truly,

Carl N. Johnson

R&D Studies applied to SCW design

Appendix A

AUTHOR	TELEPHONE NO.	FAX NO.	E-MAIL ADDRESS
ADDRESS OF SITE		WELL DRILLER/ADDRESS	
DESCRIPTION/PERFORMANCE		HVAC CONTRACTOR/ADDRESS	
HVAC DESIGN DESCRIPTION			
HVAC CAPACITY			
TYPE AND NUMBER OF HEATING/COOLING FIXTURES			
CONTROL SYSTEM DESCRIPTION			

WELL DESIGN

BLEED STRATEGY

NUMBER OF SCWs	AMOUNT OR PERCENT OF WELL FLOW	
WELL LOG DATA (INCLUDE COPY)	AQUASTAT SETPOINT	
DEPTH OF EACH WELL	DISPOSAL OF BLEED WATER	
BOREHOLE DIAMETER	WELL YIELD FLOW AT DEFINED DRAWDOWN	
WELL PUMP MFR./MODEL	GROUNDWATER FLOW FROM GEOLOGICAL DATA	
WHAT'S THE DEPTH OF THE WELL PUMP?		
DESCRIBE THE DESIGN OF THE DIP TUBE		
DEPTH OF RE-INJECTION		
DESIGN DELIVERY GPM/HEAD		
IS THERE A 2ND PUMP FOR DOMESTIC WATER USE?		
SOIL DATA, STRUCTURE AND TYPE		
ANY MONITORED DATA AVAILABLE?		
COMMENTS OR DESCRIPTION OF THE PERFORMANCE OF THE SYSTEM		