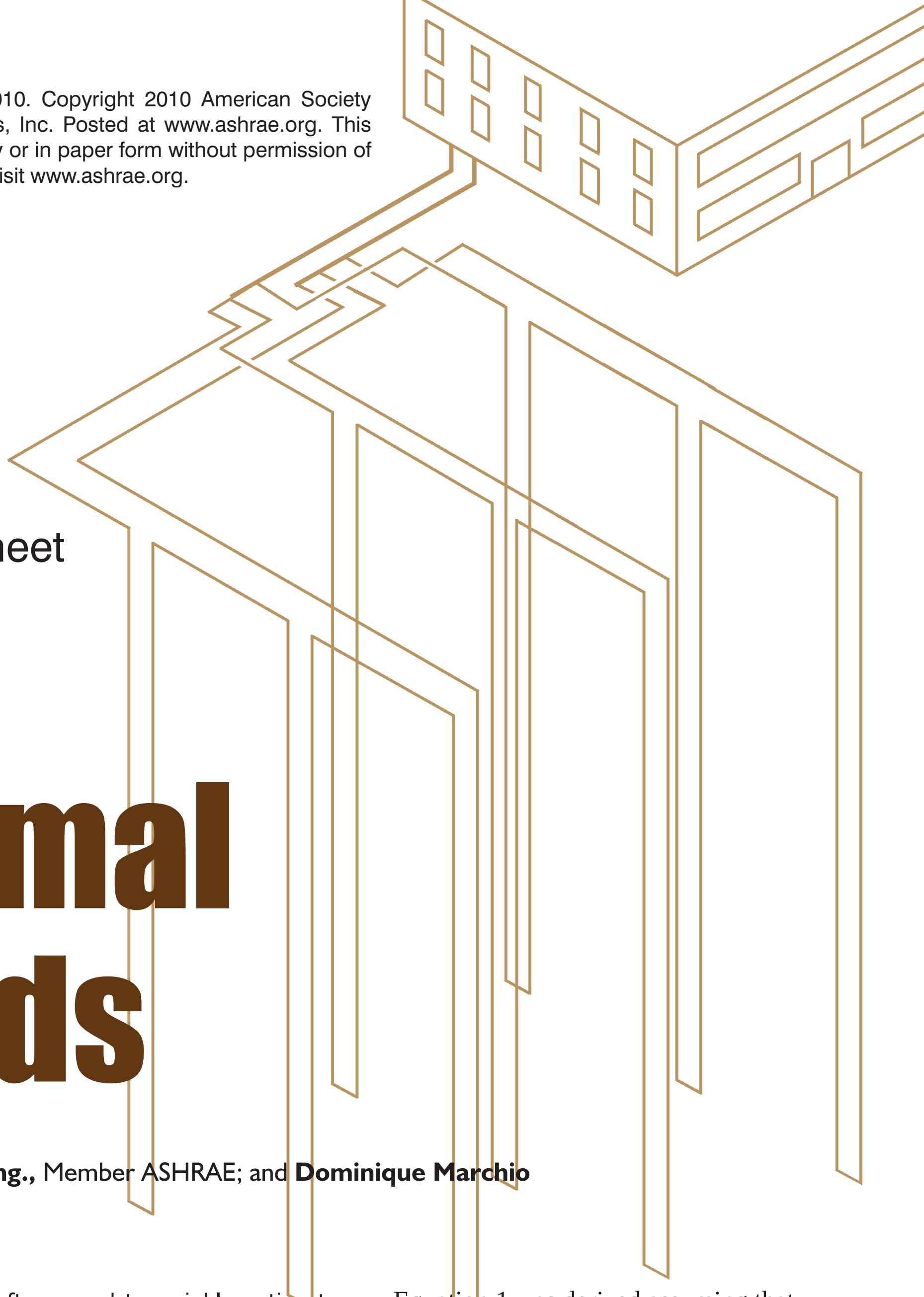


Sizing Calculation Spreadsheet

Vertical Geothermal Borefields

By **Mikael Philippe; Michel Bernier, Ph.D., P.Eng.,** Member ASHRAE; and **Dominique Marchio**

Designers of vertical geothermal systems often need to quickly estimate the total length of a borefield for a given building. One way to perform this calculation is to use the sizing equation proposed by Kavanaugh and Rafferty[1] and contained in the *ASHRAE Handbook*.[2] This equation has been recast by Bernier[3] into the following form:

$$L = \frac{q_h R_b + q_y R_{10y} + q_m R_{1m} + q_h R_{6h}}{T_m - (T_g + T_p)} \quad (1)$$

where

L is the total borehole length,

T_m is the mean fluid temperature in the borehole,

T_g is the undisturbed ground temperature,

T_p, the temperature penalty, represents a correction to the undisturbed ground temperature due to thermal interferences between boreholes (in the case of a single borehole, $T_p = 0$),

q_y, q_m and q_h represent, respectively, the yearly average ground heat load (thermal annual imbalance), the highest monthly ground load and the peak hourly ground load,

R_{10y}, R_{1m} and R_{6h} are effective ground thermal resistances corresponding to 10 years, one month and six hours ground loads, and

R_b is the effective borehole thermal resistance.

Equation 1 was derived assuming that heat transfer in the ground occurs only by conduction and that moisture evaporation or underground water movement are not significant.

As illustrated in *Figure 1*, Equation 1 is based on the worst-case scenario represented by three successive thermal pulses with durations corresponding to 10 years, one month, and six hours. These pulse durations are typically used in design.

About the Authors

Mikael Philippe is a Ph.D. candidate at the Bureau des recherches géologiques et minières in Orléans, France. **Michel Bernier, Ph.D., P.Eng.,** is a professor in the département de génie mécanique at École Polytechnique de Montréal in Montréal, Canada. He is a member of TC 6.8, Geothermal Energy Utilization. **Dominique Marchio** is a professor at the Centre Énergétique et Procédés at MINES ParisTech in Paris.

The sizing calculation spreadsheet is available for free at www.ashrae.org/borehole.xls.

The method presented here is strictly applicable only when these values are used. The amplitudes of these pulses are determined from the building load profile and the coefficient of performance of the heat pumps. The evaluations of the three effective ground thermal resistances and of the temperature penalty are not straightforward. This article proposes correlations, based on multiple calculations, to calculate these values. Furthermore, a simple way to evaluate the equivalent borehole thermal resistance, based on the work of Hellström[4] is proposed. With these correlations, a simple spreadsheet-based calculation can be carried out to obtain borehole length estimates.

In the next section, the methods used to generate the correlations are presented. This is followed by a brief description of the methodology used to evaluate R_b. Finally, two sizing examples, for single and multiple boreholes systems, are presented to demonstrate the ease of use of the proposed method. A Microsoft Excel spreadsheet accompanies this article (see link in the box above). The procedure presented here and the accompanying spreadsheet are not intended to replace commercially available borehole sizing software (which cover a larger spectrum of conditions) but to provide designers with a simple tool to guide them through *ASHRAE Handbook* calculations.

Correlations for R_{6h}, R_{1m} and R_{10y}

The effective ground thermal resistances account for transient heat transfer from the borehole wall to the far-field undisturbed ground temperature. Several ways exist to evaluate thermal resistances in the ground. In this work, the approach proposed by Kavanaugh and Rafferty[1] and contained in the *ASHRAE Handbook*[2] is used. It is based on the cylindrical heat source solution originally proposed by Carslaw and Jaeger[5] used in conjunction with temporal superposition as proposed by Ingersoll and Plass[6] and reviewed by Bernier.[7] The effective thermal resistances are expressed as follows:

$$R_{6h} = \frac{1}{k} G\left(\alpha t_{6h} / r_{bore}^2\right)$$
$$R_{1m} = \frac{1}{k}\left[G\left(\alpha t_{1m+6h} / r_{bore}^2\right) - G\left(\alpha t_{6h} / r_{bore}^2\right)\right] \quad (2)$$
$$R_{10y} = \frac{1}{k}\left[G\left(\alpha t_{10y+1m+6h} / r_{bore}^2\right) - G\left(\alpha t_{1m+6h} / r_{bore}^2\right)\right]$$

where

G-function represents the cylindrical heat source solution,

k is the ground thermal conductivity,

α is the ground thermal diffusivity, and

r_{bore} is the borehole radius (*Figure 3*).

The cylindrical heat source solution is strictly valid for one-dimensional (in the radial direction) transient heat transfer.

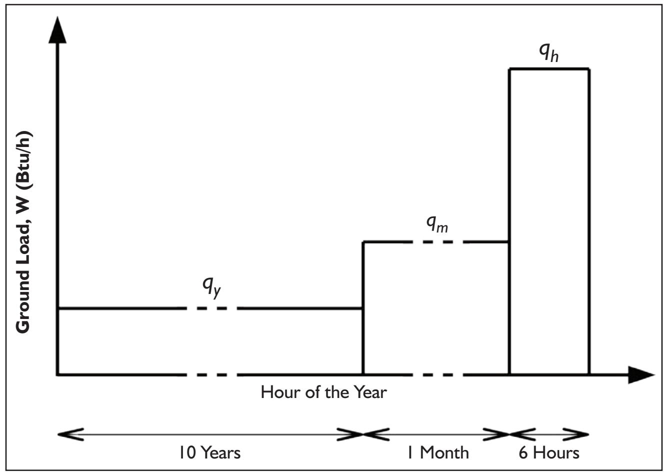


Figure 1: Three consecutive ground load pulses.

After a time period equivalent to $H^2/(90\alpha)$, where *H* is the borehole depth, Eskilson[8] has shown that axial effects start to be significant. The error introduced when using the cylindrical heat source has been calculated by Philippe, et al.[9]

Based on these results, it appears that the axial effects are only significant for the R_{10y} term and that the error remains below 5% for typical values of thermal diffusivities. More accurate solutions, such as the two-dimensional finite line source model (Eskilson[8]) could be used. These solutions are more complex to solve and the gain in accuracy in the context of an engineering approximation does not warrant their use here. In the present work, the *G*-function is calculated precisely based on the work of Baudoin.[10] Alternatively, readers can use the graphical values presented by Kavanaugh and Rafferty.[1] For each of the three effective ground resistances, R_{6h}, R_{1m} and $R_{10y,}$ a total of 48 calculations are performed over the following range of typical operating conditions:

$$0.05\ m \le r_{bore} \le 0.1\ m \quad (3)$$
$$0.025\ m^2/day \le \alpha \le 0.2\ m^2/day$$

Then, to avoid complicated calculations of the *G*-function, these results were curve-fitted in the following form:

$$R = \frac{1}{k} f\left(\alpha, r_{bore}\right)$$
$$f = a_0 + a_1 r_{bore} + a_2 r_{bore}^2 + a_3\alpha + a_4\alpha^2 + a_5\ln(\alpha) + \quad (4)$$
$$a_6\ln(\alpha)^2 + a_7 r_{bore}\alpha + a_8 r_{bore}\ln(\alpha) + a_9\alpha\ln(\alpha)$$

As shown, the resulting correlation function *f* depends only on two dimensional parameters, α and r_{bore}, given in m²/day and in m, respectively. The correlation coefficients for f_{6h}, f_{1m} and f_{10y} are given in *Table 1*.

The correlated values are compared with the calculated values in *Figure 2*. The results are plotted in terms of effective thermal resistances for a particular value of ground thermal conductivity, *k*=1 W/(m·K) [0.58 Btu/h·ft·°F]. The bottom and left axes present results in SI units while I-P units are used in the top and right

	f_{6h}	f_{1m}	f_{10y}
a_0	0.6619352	0.4132728	0.3057646
a_1	–4.815693	0.2912981	0.08987446
a_2	15.03571	0.07589286	–0.09151786
a_3	–0.09879421	0.1563978	–0.03872451
a_4	0.02917889	–0.2289355	0.1690853
a_5	0.1138498	–0.004927554	–0.02881681
a_6	0.005610933	–0.002694979	–0.002886584
a_7	0.7796329	–0.6380360	–0.1723169
a_8	–0.3243880	0.2950815	0.03112034
a_9	–0.01824101	0.1493320	–0.1188438

Table 1: Correlation coefficients for f_{6h}, f_{1m} and f_{10y}.

axes. As shown in this figure, the agreement between correlated and calculated values is very good with coefficients of correlation (R^2) equal to 99.99, 99.99 and 99.78, for f_{6h}, f_{1m} and f_{10y}, respectively. The values of f_{6h} and f_{1m} are much more sensitive to the characteristics of the soil and the borehole, while f_{10y} remains almost constant over typical ranges of values of α and r_{bore}.

Correlation for the Temperature Penalty, T_p

The temperature penalty, T_p, represents a correction applied to the ground temperature to account for the thermal interference between boreholes in a borefield. (T_p is actually a temperature difference, not an absolute temperature.) Bernier[11] has proposed a correlation to calculate T_p. This correlation is based on a correlation function, F, which depends on four parameters and takes the following form:

$$T_p = \frac{q_y}{2\pi k L} F\left(t/t_s, B/H, NB, A\right) \tag{5}$$

where

H is the borehole depth,

B is the distance between adjacent boreholes (a square mesh is assumed),

NB is the number of boreholes,

A is the geometrical aspect ratio (number of boreholes in the longest direction over the number of boreholes in the other direction), and

t_s is a characteristic time ($=H^2/9\alpha$).

The correlation function F is expressed as the sum of 37 terms with the following form:

$$F = \sum_{i=0}^{36} b_i \times c_i \tag{6}$$

with coefficients given in *Table 2*.

This correlation has some restrictions. It is valid for a constant value of B (i.e., the distance between adjacent boreholes, arranged in a square mesh, is the same throughout the bore-

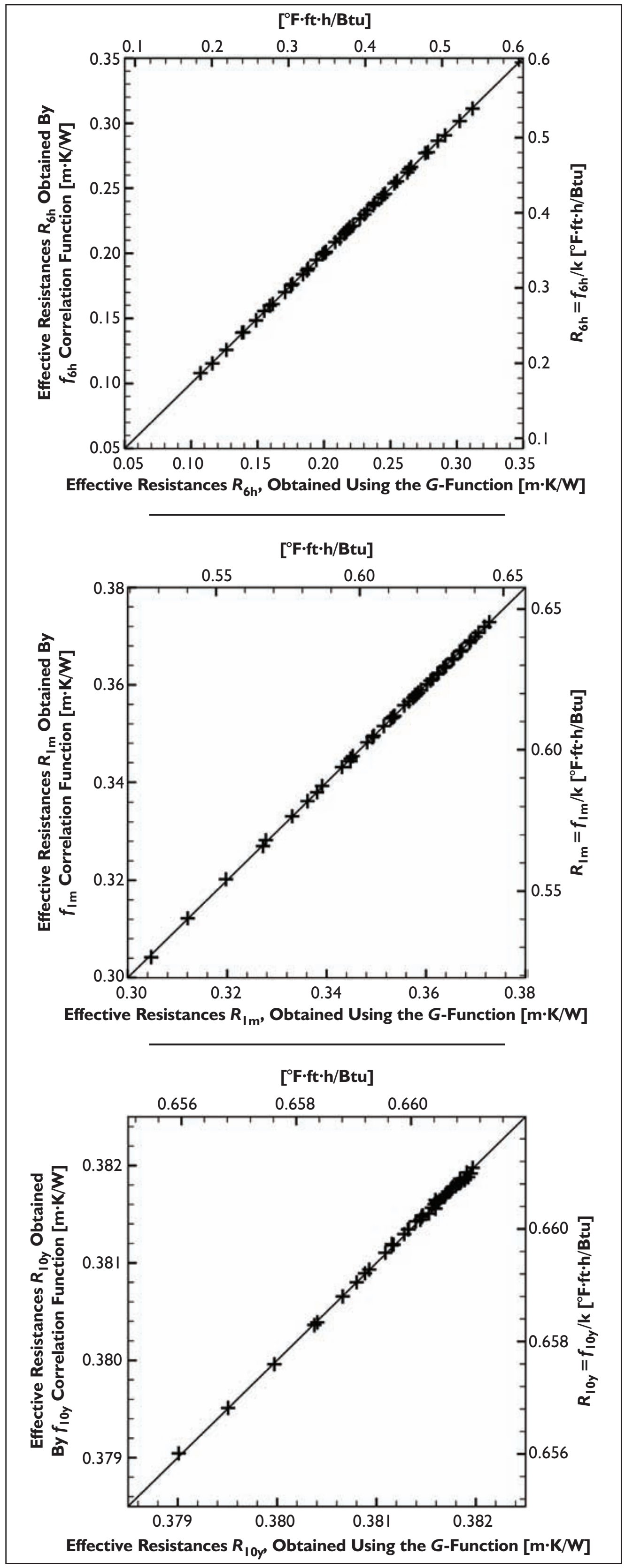


Figure 2: Comparison between the effective thermal resistances R_{6h}, R_{1m}, and R_{10y} obtained by calculation and correlation for k = 1 W/(m·K) [0.578 Btu/h·ft·°F].

2008 DEALER DESIGN AWARDS
the NEWS | GOLD

Based on looks alone, the answer is simple. The stylish one on the left is LG's new Art Cool™ Mirror Inverter Air Conditioning System. The unique design with its sleek mirrored finish also has a variety of attractive panel options to complement any room's décor.

But good looks are just part of what sets LG's Art Cool apart. Their innovative new inverter technology means that it runs quiet and has an energy efficient rating up to 19.7 SEER. And that saves you money. What's more, LG Art Cool's duct-free design makes installation fast and economical. And with the wide variety of cooling capacities available, it's easy to find a unit that matches almost any size room.

Discover the full line of LG products at www.LGusa.com.

Innovative Comfort Solutions

LG Life's Good

www.LGusa.com

www.info.hotims.com/30917-26

i	b_i	c_i
0	7.8189E+00	1
1	–6.4270E+01	B/H
2	1.5387E+02	$(B/H)^2$
3	–8.4809E+01	$(B/H)^3$
4	3.4610E+00	$\ln(t/t_s)$
5	–9.4753E–01	$(\ln[t/t_s])^2$
6	–6.0416E–02	$(\ln[t/t_s])^3$
7	1.5631E+00	NB
8	–8.9416E–03	NB^2
9	1.9061E–05	NB^3
10	–2.2890E+00	A
11	1.0187E-01	A^2
12	6.5690E-03	A^3
13	–4.0918E+01	$(B/H) \times \ln(t/t_s)$
14	1.5557E+01	$(B/H) \times (\ln[t/t_s])^2$
15	–1.9107E+01	$(B/H) \times NB$
16	1.0529E–01	$(B/H) \times NB^2$
17	2.5501E+01	$(B/H) \times A$
18	–2.1177E+00	$(B/H) \times A^2$
19	7.7529E+01	$(B/H)^2 \times \ln(t/t_s)$
20	–5.0454E+01	$(B/H)^2 \times (\ln[t/t_s])^2$
21	7.6352E+01	$(B/H)^2 \times NB$
22	–5.3719E–01	$(B/H)^2 \times NB^2$
23	–1.3200E+02	$(B/H)^2 \times A$
24	1.2878E+01	$(B/H)^2 \times A^2$
25	1.2697E–01	$\ln(t/t_s) \times NB$
26	–4.0284E-04	$\ln(t/t_s) \times NB^2$
27	–7.2065E–02	$\ln(t/t_s) \times A$
28	9.5184E–04	$\ln(t/t_s) \times A^2$
29	–2.4167E–02	$(\ln[t/t_s])^2 \times NB$
30	9.6811E–05	$(\ln[t/t_s])^2 \times NB^2$
31	2.8317E–02	$(\ln[t/t_s])^2 \times A$
32	–1.0905E–03	$(\ln[t/t_s])^2 \times A^2$
33	1.2207E–01	$NB \times A$
34	–7.1050E–03	$NB \times A^2$
35	–1.1129E–03	$NB^2 \times A$
36	–4.5566E–04	$NB^2 \times A^2$

Table 2: Coefficients b_i *and* c_i *for the* F *correlation.*

field). Furthermore, the other parameters are restricted to the following ranges:

$$\begin{gathered} -2 \le \ln\left(t/t_s\right) \le 3 \\ 4 \le NB \le 144 \\ 1 \le A \le 9 \\ 0.05 \le B/H \le 0.1 \end{gathered} \qquad (7)$$

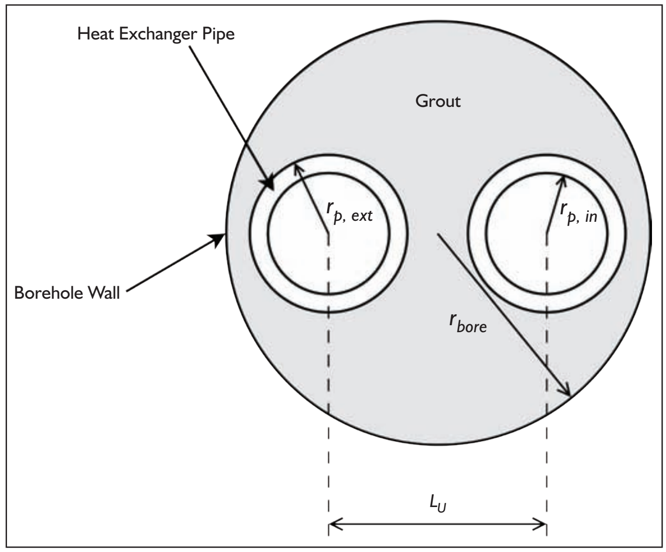


Figure 3: Cross-section of geothermal vertical borehole.

Bernier, et al.,[11] report that the difference in the T_p value when using Equation 6 is below 10% for most operating conditions compared to the standard g-functions of Eskilson.[8] As shown in Equation 7, the correlation is valid for $NB \ge 4$. Borefields with two and three boreholes are not covered with the approach proposed here. For such cases, the temperature penalty must be calculated by the method proposed by Bernier[11] based on the work of Eskilson.[8] However, borefields with two or three boreholes usually have small values of T_p as there is less borehole thermal interaction.

Calculation of R_b

A cross-section of a typical single U-tube geothermal borehole is shown in *Figure 3*. Typically, the borehole is filled with a grout to improve heat transfer and to avoid possible contamination between different aquifers. T_m, the average fluid temperature between the two legs of the U-tube, is assumed to be constant along the depth of the borehole and, therefore, equal to the average of the fluid inlet and outlet temperatures to the heat pumps ($T_m=(T_{in,HP}+T_{out,HP})/2$). The effective borehole thermal resistance R_b is the thermal resistance between the borehole wall and the fluid in the pipes (*Figure 3*). The effective borehole thermal resistance is based on three elementary effective thermal resistances and is given by:

$$R_b = R_g + \frac{R_p + R_{conv}}{2} \qquad (8)$$

The three effective thermal resistances, R_{conv}, R_p and R_g, are, respectively, the convective resistance inside each tube, the conduction resistance for each tube and the grout resistance. They are obtained using the analytical equation proposed by Hellström.[4] The three thermal resistances have the following expressions:

$$R_{conv} = \frac{1}{2\pi r_{p,in} h_{conv}} \qquad (9)$$

$$R_p = \frac{\ln\left(r_{p,ext} / r_{p,in}\right)}{2\pi k_{pipe}} \quad (10)$$

$$R_g = \frac{1}{4\pi k_{grout}} \left[\ln\left(\frac{r_{bore}}{r_{p,ext}}\right) + \ln\left(\frac{r_{bore}}{L_U}\right) + \frac{k_{grout} - k}{k_{grout} + k} \ln\left(\frac{r_{bore}^4}{r_{bore}^4 - \left(\frac{L_U}{2}\right)^4} \right) \right] \quad (11)$$

where

h_{conv} is the film convection coefficient,

$r_{p,in}$ and $r_{p,ext}$ are the inner and outer radii of the pipe,

k_{pipe} is the thermal conductivity of the pipe material,

k_{grout} is the thermal conductivity of the grout,

k is the ground thermal conductivity, and

L_U is the center-to-center distance between the two pipes (*Figure 3*).

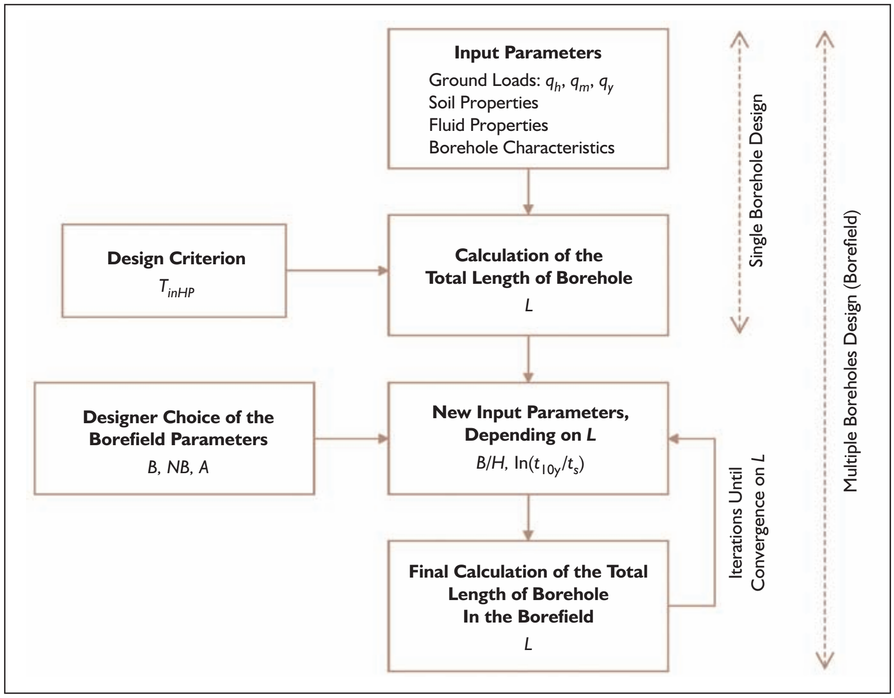


Figure 4: Flowchart of the calculation procedure for boreholes sizing.

Application Cases

Equations 1 to 11 have been implemented in an Excel spreadsheet. The calculation procedure for designing a single borehole or a borefield is illustrated in the flowchart presented in *Figure 4*. The spreadsheet can either be used for heating or cooling applications with proper signs for ground loads (positive ground loads correspond to heat rejection into the ground). The use of the spreadsheet will be illustrated using two examples for a single borehole and for a borefield. Results will be compared with those obtained from more sophisticated software tools and from data found in the literature.

As shown in *Figure 5*, there are four major parts in the spreadsheet: first set of inputs; first set of results; second set of inputs; and final results (which includes five sets of iterations). The iterations are required for multiple borehole configurations as T_p depends on H, which is not known *a priori*.

Single Borehole

The first application is for a single borehole in a cooling-dominated building. The three ground thermal pulses are 12 kW (40,000 Btu/h), 6 kW (20,000 Btu/h) and 1.5 kW (5,000 Btu/h), respectively. This is roughly equivalent to a 2.5-ton (8.8 kW) heat pump that rejects 12 kW into the ground at peak conditions. The monthly and yearly pulses can be estimated using hourly simulation results or equivalent full load operating hours.

Using this last method, it is estimated here that during the peak month, the heat pump operates half the time, so the monthly ground load is 6 kW. Finally, on an annual basis, the net amount of heat rejected into the ground is equivalent to a heat pump operating one-eighth of the time, which corresponds to 1.5 kW.

Then, ground properties and fluid thermal capacity are entered, as well as the total mass flow rate per kW of peak hourly ground load. The maximum (in cooling) or minimum (in heating) heat pump inlet temperature acceptable at peak conditions is entered next. This value, in fact, is the design criterion for sizing the borefield.

The next block of inputs concerns the borehole characteristics from the borehole radius to the internal film coefficient. The block for the first set of results shows intermediate results on all effective thermal resistances, as well as the total length, which is 151.7 m (498 ft) in this case. The heat pump outlet temperature as well as the average fluid temperature in the borehole also are provided. They are obtained through an energy balance on the borehole. In the case of a single borehole, calculations stop here as there is no borehole thermal interference.

It is interesting to note the impact of a few key parameters. For example, in cooling mode, if the undisturbed ground temperature is 20°C (68°F) (instead of 15°C [59°F]), the length increases to 185.2 m (608 ft), a 22% increase. The last two values in the borehole characteristics block, L_U and h_{conv} have a relatively large impact on the effective borehole resistance (R_b) and, consequently, on the borehole length. For example, when the distance between the pipes is reduced to a point where the pipes are touching each other, i.e., L_u is reduced from 0.0511 to 0.0334 m (2 in. to 1.3 in.), the value of R_b increases from 0.120 to by 0.143 m·K/W) [0.246 °F·ft·h/Btu] (an 18% increase with a corresponding increase of the total length of 6.5% from 151.7 to 161.6 m [498 ft to 530 ft]). For turbulent flows, h_{conv} is usually above

1000 W/(m^2·K) [176 Btu/h·ft^2·°F] while for laminar flows it is generally below 100 W/(m^2·K) [17.6 Btu/h·ft^2·°F]. In the present case, everything else being equal, a laminar flow with h_{conv} = 100 W/(m^2·K) [17.6 Btu/h·ft^2·°F] would lead to a required borehole length of 174.5 m (573 ft).

Finally, the proposed approach was checked against the DST model,[12] which is often considered as a reference software tool for simulating ground heat exchangers. In this test, the DST model is run with three consecutive constant ground load pulses of 10 years, one month, and six hours using the data given in the first set of inputs. Results from the DST model give a total length of 150 m (492 ft), which is in good agreement with the value of 151.7 m (498 ft) obtained with the proposed approach.

Multiple Boreholes

In this second example, the data are provided by Shonder, et al.[14] They are relative to a school and have been used to compare five different design programs against each other. This heating application uses a 12 × 10 borefield with 6.1 m (20 ft) spacing between boreholes. Much of the data in the first set of inputs is extracted from the comparison study[14] except for the center-to-center distance between pipes that is assumed to be equal to 0.0471 m (1.85 in). This corresponds to a case where the distance between the pipes is the same as the distance between the pipes and the borehole wall. After analyzing test data achieved on various boreholes Remund[13] recommended this spacing for such calculations.

For multiple boreholes, the procedure is a little more complicated than for single boreholes due to the presence of T_p in Equation 1. This temperature penalty depends on the borehole depth, which is the unknown *a priori*. An iterative procedure is required. The following three-step procedure is recommended to properly account for T_p.

First, calculations should be performed by assuming that T_p is zero as for a single borehole. This will lead to an approximate value of the total length of the borefield. In the present example, the approximate length is 9899 m (32,470 ft).

Based on this approximate value, the designer enters the second set of inputs, i.e., B (distance between the boreholes), NB (number of boreholes) and A (aspect ratio of the borefield). Depending on the available ground area and the ground

		UNITS	Single borehole	Multiple boreholes
1st SET OF INPUTS				
Ground loads				
peak hourly ground load	q_h	W	12000	-392250
monthly ground load	q_m	W	6000	-100000
yearly average ground load	q_y	W	1500	-1762
Ground properties				
thermal conductivity	k	$W.m^{-1}K^{-1}$	2	2.25
thermal diffusivity	α	$m^2.day^{-1}$	0.086	0.068
Undisturbed ground temperature	T_g	°C	15	12.41
Fluid properties				
thermal heat capacity	Cp	$J.kg^{-1}.K^{-1}$	4200	4000
total mass flow rate per kW of peak hourly ground load	m_{fls}	$kg.s^{-1}.kW^{-1}$	0.050	0.074
max/min heat pump inlet temperature	T_{inHP}	°C	40.2	4.44
Borehole characteristics				
borehole radius	r_{bore}	m	0.060	0.054
pipe inner radius	r_{pin}	m	0.0137	0.0137
pipe outer radius	r_{pext}	m	0.0167	0.0167
grout thermal conductivity	k_{grout}	$W.m^{-1}.K^{-1}$	1.50	1.73
pipe thermal conductivity	k_{pipe}	$W.m^{-1}.K^{-1}$	0.42	0.45
center-to-center distance between pipes	L_U	m	0.0511	0.0471
internal convection coefficient	h_{conv}	$W.m^{-2}.K^{-1}$	1000	1000
1st SET OF RESULTS				
Calculation of the effective borehole thermal resistance				
convective resistance	R_{conv}	$m.K.W^{-1}$	0.012	0.012
pipe resistance	R_p	$m.K.W^{-1}$	0.076	0.071
grout resistance	R_g	$m.K.W^{-1}$	0.076	0.060
effective borehole thermal resistance	R_b	$m.K.W^{-1}$	0.120	0.102
Calculation of the effective ground thermal resistances				
short term (6 hours pulse)	R_{6h}	$m.K.W^{-1}$	0.114	0.101
medium term (1 month pulse)	R_{1m}	$m.K.W^{-1}$	0.180	0.160
long term (10 years pulse)	R_{10y}	$m.K.W^{-1}$	0.191	0.170
Total length calculation assuming no borehole thermal interference				
heat pump outlet temperature	T_{outHP}	°C	45.0	1.1
average fluid temperature in the borehole	T_m	°C	42.6	2.8
total length	L	m	151.7	9899.3
2nd SET OF INPUTS				
Borefield characteristics				
distance between boreholes	B	m		6.1
number of boreholes	NB	-		120
borefield aspect ratio	A	-		1.2
FINAL RESULTS				
Total length calculation (with Tp)				
1st iteration				
distance-depth ratio	B/H	-		0.074
logarithm of dimensionless time	$ln(t_{10y}/t_s)$	-		-1.120
temperature penalty	T_p	°C		-0.240
total borefield length	L	m		10151.5
2nd iteration				
distance-depth ratio	B/H	-		0.072
logarithm of dimensionless time	$ln(t_{10y}/t_s)$	-		-1.170
temperature penalty	T_p	°C		-0.238
total borefield length	L	m		10149.7
3rd iteration				
distance-depth ratio	B/H	-		0.072
logarithm of dimensionless time	$ln(t_{10y}/t_s)$	-		-1.170
temperature penalty	T_p	°C		-0.238
total borefield length	L	m		10149.7
4th iteration				
distance-depth ratio	B/H	-		0.072
logarithm of dimensionless time	$ln(t_{10y}/t_s)$	-		-1.170
temperature penalty	T_p	°C		-0.238
total borefield length	L	m		10149.7
5th iteration				
distance-depth ratio	B/H	-		0.072
logarithm of dimensionless time	$ln(t_{10y}/t_s)$	-		-1.170
temperature penalty	T_p	°C		-0.238
total borefield length	L	m		10149.7
Final results				
total borefield length	L	m		10149.7
borehole depth	H	m		84.6

Figure 5: Spreadsheet for designing vertical geothermal boreholes—examples of results.

characteristics, the designer can opt for a more or less compact configuration. In the present case, B=6.1 m (20 ft), NB=120, A=1.2 which are the values chosen by the designer of the Maxey Elementary School.[14] After this second set of inputs is entered, the final results block of the spreadsheet shows a set of five iterations in which T_p is reevaluated based on the new length calculations. This process converges rapidly and five iterations are usually sufficient. In the present case, the total borefield length is 10 150 m (33,290 ft) with a corresponding borehole depth of 84.6 m (277 ft). The temperature penalty T_p is –0.24°C (–0.43 °F) after 10 years of operation. This is a relatively small value of borehole interference, which is due to the small annual thermal imbalance in the ground (1.762 kW). The design programs tested by Shonder, et al.,[14] gave results between 65 m (213 ft) and 87 m (285 ft). Thus, the results given by the proposed procedure are in good agreement with other more sophisticated software tools.

Conclusion

A simple design procedure for single and multiple borehole configurations is presented. The procedure is based on the borehole sizing equation given in *ASHRAE Handbook*.[2] Simple algebraic correlations (Equation 4), based on a multitude of calculations, are proposed to calculate effective ground thermal resistances. These correlations, which are much simpler to use than the cylindrical heat source solution, are shown to be in excellent agreement with calculated values. Borehole thermal interference is accounted for using a correlation developed by Bernier, et al.,[11] to evaluate the temperature penalty (Equation 6). Finally, the approach suggested by Hellström[4] is used to evaluate the effective borehole resistance (Equation 8).

Designers using this method should be aware of its limitations. First, it is strictly valid for successive ground load pulse durations of 10 years, one month and six hours. Any significant deviations from these periods, especially the six-hour period, may require the use of commercially available borehole sizing software.[15] Second, the range of applicable parameters for the determination of T_p is limited to values indicated in Equation 7. In the case of multiple boreholes, a simple iterative calculation is required as the temperature penalty depends on borehole depth, which is unknown *a priori*.

The proposed procedure is implemented in a spreadsheet. Two examples are provided, which show that the proposed approach is in good agreement with recognized borefield design software.

References

1. Kavanaugh, S.P., K. Rafferty. 1997. *Ground-Source Heat Pumps: Design of Geothermal Systems for Commercial and Institutional Buildings*, Chap. 3. Atlanta: ASHRAE.
2. *2007 ASHRAE Handbook—HVAC Applications*, Chap. 32.
3. Bernier, M. 2006. “Closed-loop ground-coupled heat pump systems.” *ASHRAE Journal* 48(9):12–19.
4. Hellström, G. 1991. “Ground Heat Storage—Thermal Analyses of Duct Storage Systems.” Ph.D. Thesis. University of Lund, Lund, Sweden.
5. Carslaw, H.S., J.C. Jaeger. 1947. *Conduction of Heat in Solids*. Oxford, UK: Oxford University Press, p. 510.
6. Ingersoll, L.R., H.J. Plass. 1948. “Theory of the ground pipe heat source for the heat pump.” *Heating, Piping and Air Conditioning* 20(7):119–122.
7. Bernier, M. 2000. “A review of the cylindrical heat source method for the design and analysis of vertical ground-coupled heat pump systems.” *4th International Conference on Heat Pumps in Cold Climates*, p. 1–14.
8. Eskilson, P. 1987. “Thermal Analysis of Heat Extraction Boreholes.” Ph.D. Thesis. University of Lund, Lund, Sweden.
9. Philippe, M., M. Bernier, D. Marchio. 2009. “Validity ranges of three analytical solutions to heat transfer in the vicinity of single boreholes.” *Geothermics* 38:407–413.
10. Baudoin, A. 1988. “Stockage intersaisonnier de chaleur dans le sol par batterie d’échangeurs baïonnette verticaux: modèle de prédimensionnement. ” Ph.D. Thesis. University of Reims, Reims, France.
11. Bernier, M., A. Chala, P. Pinel. 2008. “Long-term ground-temperature changes in geo-exchange systems.” *ASHRAE Transactions* 114(2):342–350.
12. Hellström, G. 1989. “Duct Ground Heat Storage Model – Manual for Computer Code. University of Lund, Lund, Sweden.
13. Remund, C.P. 1999. “Borehole thermal resistance: laboratory and field studies.” *ASHRAE Transactions* 105(1): 439–445.
14. Shonder, J.A., et al. 2000. “A comparison of vertical ground heat exchanger design software for commercial applications.” *ASHRAE Transactions* 106(1):831–842.
15. Hellström, G., B. Sanner. 2001. “PC-programs and modelling for borehole heat exchanger design.” *Proceedings of International Geothermal Days.*●

83% CONSTANT EFFICIENCY

Introducing the new

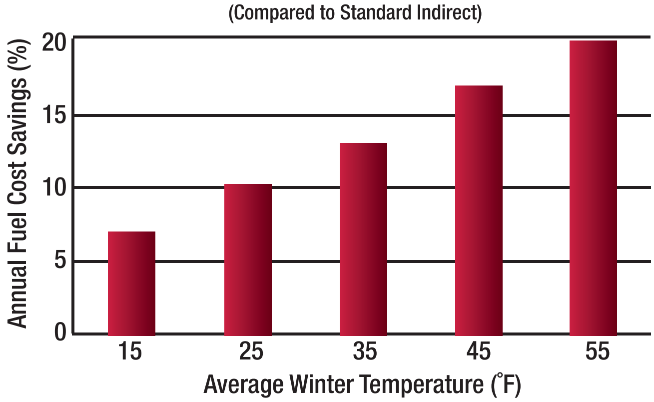
Indirect Fired Heater

by CAPTIVEAIRE

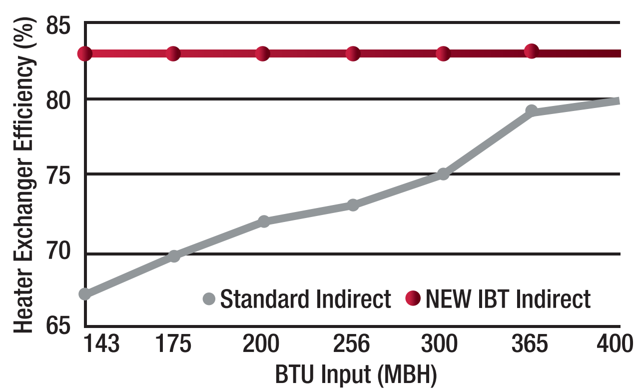
Advertisement formerly in this space.

Annual Fuel Savings @ 83% Efficiency

(Compared to Standard Indirect)



Indirect Fired Energy Comparison



CaptiveAire's Modular Indirect Fired Bent Tube Heater (IBT) is designed to deliver clean air into an indoor environment. The push-through design ensures that combustion fumes will not enter the fresh air stream.

- The IBT achieves a 83% Constant Efficiency over Entire Gas Firing Range
- Full electronic gas modulation with a variable speed power-vent Motor
- Economizer Inlet Air Thermostat
- Electronic Vernier Modulation for exact temperature control
- Performance up to 20,000 CFM and max BTU input (MBH) of 1,600
- 28:1 Max Turndown

4641 Paragon Park Road, Raleigh, NC 27616 | 800.334.9256 | www.captiveaire.com/IBT

CAPTIVEAIRE

www.info.hotims.com/30917-15