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Design of borehole heat exchangers for ground source heat pumps: a comparison between two methods

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Abstract

Different methods for the design of Borehole Heat Exchangers are available, as reported for example in the Italian standard UNI 11466. Therefore the question arises about the impact of the design methodology on the final result and its sensitivity to the main design and input parameters.

In this paper two common design approaches, namely the ASHRAE analytical method by Kavanaugh and Rafferty and the GLHEPRO commercial tool, based on g-functions method by Eskilson, are taken into account. The two methods are used to design a BHE field for a GSHP system in two case studies, namely a small-scale residential and a medium-scale commercial building. Moreover, a sensitivity analysis for each method is carried out, considering the influence of the main design choices and uncertainties on the required inputs.

The comparison between the two methods shows that ASHRAE tends to overestimate, up to 27%, the BHE size compared to GLHEPRO. Among the parameters investigated, the heat pump size and the BHE layout modestly affect the final BHE size. In turn, the thermal-vector fluid temperatures on the ground side of the heat pump, the single/double U pipe configuration, the distance among adjacent boreholes and the ground thermal conductivity result in the major influence. In particular it is shown that the uncertainty in the ground thermal conductivity and the choice of the fluid temperatures have a comparable impact on the final sizing as the choice of the sizing method.

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1. Introduction

Ground Source Heat Pumps are often installed in high-energy performance and Zero Energy Buildings, since they operate with a high COP and, according to EU Directive 28/2009, they are renewable energy based. However their long-term operation relies on a proper design of the Boreholes Heat Exchanger (BHE), made up of vertical U-pipes drilled up to about 100 m in the ground. At the same time, the BHE size represents the major initial cost and thus the main economic barrier to the widespread of such systems. Therefore the BHE design phase and the sizing method are crucial. In this paper a comparison between two common design approaches, namely the ASHRAE method [1] and the GLHEPRO [2] commercial tool, is performed, in order to understand the impact of the design method on the BHE size. Moreover a sensitivity analysis is carried out for both methods, with the aim to assess the influence of the main design inputs and hypothesis.

2. Design methods

2.1. ASHRAE method

The ASHRAE method is an analytical one. The sizing equations are basically obtained by solving for the total BHE length L the following steady state equation for the heat transfer in the ground:

$$Q = L \frac{(T_g - T_f)}{R} \quad (1)$$

where Q is the heat rate, T_g the undisturbed ground temperature, T_f the average fluid temperature and R is the BHE thermal resistance. The total length for the heating (L_h) and the cooling (L_c) mode are calculated separately according to equations (2) and (3) respectively:

$$L_h = \frac{Q'_a R_{ga} + Q'_{g,h,D} (R_b + PLF_{m,h,D} R_{gm} + R_{gd} F_{sc})}{T_g - \left(\frac{T_{f,in} - T_{f,out}}{2} \right) - T_p} \quad (2)$$

$$L_c = \frac{Q'_a R_{ga} + Q'_{g,c,D} (R_b + PLF_{m,c,D} R_{gm} + R_{gd} F_{sc})}{T_g - \left(\frac{T_{f,in} - T_{f,out}}{2} \right) - T_p} \quad (3)$$

where:

- Q'_a is the net annual heat transfer rate to the ground;
- $Q'_{g,h,D}$ and $Q'_{g,c,D}$ are the design heat transfer to the ground in the heating/cooling mode;
- R_{ga} , R_{gm} and R_{gd} are the effective thermal resistances referred to annual, monthly and daily heat pulses;
- R_b is the effective borehole thermal resistance;
- $PLF_{m,h,D}$ and $PLF_{m,c,D}$ are the Partial Load Factors in the heating/cooling design months;
- F_{sc} is the short circuit heat loss factor, accounting for the thermal interference between flow and return pipes;
- $T_{f,in}$ and $T_{f,out}$ are the fluid temperature at the heat pump inlet and outlet;
- T_p is the temperature penalty.

Heat rates and temperature penalties are assumed to be positive in the heating mode. The recommended design BHE length L_d is the largest between L_h and L_c . By looking at equations (2) and (3) it can be noticed that three thermal pulses are considered: the term $Q'_a R_{ga}$ takes into account the annual thermal imbalance in the ground and its long-term effects, $Q'_{g,h,D} PLF_{m,h,D} R_{gm}$ takes into account the average monthly rate effects while $Q'_{g,h,D} R_{gd} F_{sc}$ the impact of the maximum heat rate for a short period in a design day. A more detailed description of the method can be found in [1]. Here it is worth mentioning that the Infinite Cylindrical Source (ICS) model [3] is used in particular to evaluate the ground effective thermal resistances. Moreover an approximate solution of the Infinite Line Source (ILS) problem [3] is used to calculate the temperature penalty, that takes into account the interference between adjacent boreholes. In the Italian standard UNI 11466 [4] an iterative procedure for the application of the ASHRAE

method is outlined. At first, in order to obtain the annual heat transfer rate to the ground, design COP and EER of the heat pump are used instead of seasonal efficiencies. The achieved design length is used to calculate monthly operating fluid temperatures on the ground side (by solving equations (2) and (3) for the average fluid temperature) and then monthly and seasonal efficiencies of the heat pump. Then a second calculation step is carried out adopting seasonal efficiencies, so that a new design length is achieved to be compared with the first step value, in order to decide whether to stop or to repeat the calculation. Therefore the outputs of the method are the design length L_d and the seasonal efficiencies SCOP and SEER.

2.2. GLHEPRO tool

GLHEPRO is a commercial tool for the design of vertical BHE, based on the g-functions method developed by Eskilson [5]. The g-functions are a set of non-dimensional temperature response factors obtained combining analytical and numerical solutions. G-functions allow evaluating the temperature change at the borehole wall in response to a step heat pulse, as shown in equation (4):

$$T_b = T_g + \sum_{i=1}^n \frac{q'_i - q'_{i-1}}{2\pi\lambda_g} g\left(\frac{t_n - t_{i-1}}{t_s}, \frac{r_b}{H}, \frac{B}{H}, N_b\right) \quad (4)$$

where T_b is the borehole wall temperature, q'_i the step rejection pulse, λ_g the ground thermal conductivity. The g-functions depend on a non-dimensional time ($t_s = H^2/9\alpha$ being a characteristic time scale depending on the ground thermal diffusivity α), on the ratio of the borehole radius r_b to the borehole depth H , on the ratio of the borehole spacing B to H and on the number of boreholes N_b . They are pre-calculated and stored for a wide range of borehole configurations. However Eskilson's g-functions are valid for long times, namely one week or more. Therefore Spitler [2] developed short-time g-functions based on an approximated solution of the ILS to be used in GLHEPRO.

In GLHEPRO building monthly and peak loads are transformed into ground monthly and peak pulses on the basis of a heat pump performance curve and of a first guess for the fluid temperature at the heat pump inlet on the ground side. A starting value H_0 for the boreholes depth is assumed and g-functions are then used to calculate the borehole wall temperature. The latter is used to derive the average fluid temperature in the BHE on the ground side and then an iterative procedure can start. It has to be noticed that SCOP and SEER are not output by GLHEPRO, but they can be easily derived from the operating fluid temperatures on the ground side.

2.3. Comparing the inputs

Some differences between the two approaches may also be found in the required inputs, namely:

- regarding the building: ASHRAE requires peak loads only for the design heating/cooling month, while GLHEPRO allows entering peak loads for each month. Further GLHEPRO requires the peak load duration;
- regarding the heat pump: partial load operation is taken into account in ASHRAE, while only full-load operation curves are input in GLHEPRO;
- regarding fluid temperatures on the ground side: in ASHRAE heat pump inlet and outlet temperatures in design conditions are required, while in GLHEPRO the seasonal minimum and maximum inlet are input.

3. BHE sizing

The ASHRAE method and the GLHEPRO tool are used to size the BHE in two case studies (see Table 1), representing a small and a medium scale application for a residential and an office building respectively. The building monthly energy needs and peak loads of the two case studies are taken from the examples reported in [4]. The two buildings are equipped with different emission systems, namely radiant panels and fan coils, leading to different temperature levels on the heat pump demand side. The BHEs are assumed to be drilled in an unconsolidated ground made up of wet silt/clay layers with a thermal conductivity $\lambda_g = 1.7$ W/(m.K), a thermal diffusivity $\alpha = 8.3 \cdot 10^{-7}$ m²/s and an undisturbed ground temperature $T_g = 13.1^\circ\text{C}$. Single or double U-pipes are

inserted in boreholes with $r_b = 6$ cm, backfilled with a bentonite/quartzite mix grout with $\lambda_{gr} = 1.47$ W/(m.K). The thermal carrier fluid is an antifreeze water solution with 20% ethylene glycol.

Table 1. Case studies

Building	Heating peak load (kW)	Cooling peak load (kW)	Emission system
Residential	8.8	7.7	Radiant panels
Office	60	80	Fan coils

For each case study and for each sizing method a parametric study is carried out by varying some relevant design parameters, namely the ground thermal conductivity and the fluid temperature levels at the ground side. For the residential case study the impact of the heat pump size and of the single/double U pipe configuration is also tested. In turn for the office case study the boreholes distance and layout are also varied.

3.1. Residential case study

The residential case study is heating dominated and thus the resulting design length is the heating mode one. Table 2 reports the relevant input parameters for each case generated and some calculation outputs, namely R_b , SCOP, SEER and L_d obtained with the two methods. The heating mode fluid temperature at the heat pump outlet on the BHE side is reported.

Table 2. residential case: parametric study

Case	λ_g [W/(m.K)]	U-pipe	Heat pump	$T_{f,out}$ [°C] (heating)	ASHRAE/GLHEPRO				
					R_b [m.K/W]	SCOP	SEER	L_d [m]	L_d difference [%]
R1	1.7	single	BWR MTD2 0031	2	0.14/0.13	3.7/5.3	4.8/7.2	250/210	16
R2	1.7	single	BWR MTD2 0031	5	0.14/0.13	3.9/5.5	5.3/7.7	409/352	14
R3	1.7	single	BWR MTD2 0031	0	0.14/0.12	3.6/5.2	4.4/7.0	211/179	15
R4	1.1	single	BWR MTD2 0031	2	0.14/0.13	3.7/5.2	4.8/7.0	301/250	17
R5	2.4	single	BWR MTD2 0031	2	0.14/0.12	3.7/5.3	4.9/7.3	215/180	16
R6	3.1	single	BWR MTD2 0031	2	0.14/0.12	3.7/5.3	4.9/7.3	195/164	16
R7	1.7	single	BWR MTD2 0041	2	0.14/0.12	3.5/5.3	4.3/7.2	257/210	18
R8	1.7	double	BWR MTD2 0031	2	0.07/0.11	3.7/4.7	5.0/8.3	198/192	3

Considering R1 as the base case, R2 and R3 investigate the impact of the fluid temperature at the heat pump outlet in the heating mode. Looking at the ASHRAE method results first, by passing from 2°C to 5°C, L_d increases by 64%; by passing from 2°C to 0°C, L_d decreases by 16%. A similar sensitivity is achieved with the GHEPRO method: L_d increases by 68% and decreases by 15% respectively. The impact of the fluid temperature levels on the energy efficiency is less relevant, although worthwhile: according to ASHRAE method the SCOP increases by 10% in R2 case and decreases by 5% in R3 case. Clearly operating at higher fluid temperatures on the ground side in winter rises the SCOP but implies a larger BHE. In cases R4, R5 and R6 the ground thermal conductivity is varied between 1.1 W/(m.K) and 3.1 W/(m.K), namely the lower and higher limits for this kind of ground according to [4]. A relevant influence of λ_g on the BHE size is found for both design methods (Figure 1b): e.g. according to GLHEPRO L_d can vary from a minimum of 164 m (R6) to a maximum of 250 m (R4), corresponding to -22% and +19% with respect to the base case (R1). On the contrary a negligible impact on the SCOP can be noticed.

In case R7 the heat pump heating capacity is increased, by keeping the same brand. A modest influence on the BHE size is found for both sizing methods. Regarding the energy efficiency, oversizing the heat pump leads to a poorer SCOP (-6%) and SEER (-11%) according to ASHRAE method. In turn according to GLHEPRO no variation

in the energy performance can be found. The different results are due to the fact that partial load operation for the heat pump is taken into account in ASHRAE approach and not in GLHEPRO tool.

In case R8 a double U-pipe is adopted. Therefore, with respect to the base case, L_d decreases by 21% and 9% according to ASHRAE and GLHEPRO respectively. The different impact of the U-pipe configuration in the two methods can be explained by considering the different approaches adopted for the calculation of the borehole resistance R_b [4, 6], so that the decrease in the R_b value is larger in the ASHRAE/UNI 11466 approach than in GLHEPRO (see again Table 2).

By comparing in general the sizings obtained with the two methods (Figure 1a), we can see that ASHRAE tends to overestimate the BHE length compared to GLHEPRO. The difference in L_d ranges between 14 and 18%, apart for the case with the double U-pipe where the differences reduces to 3%.

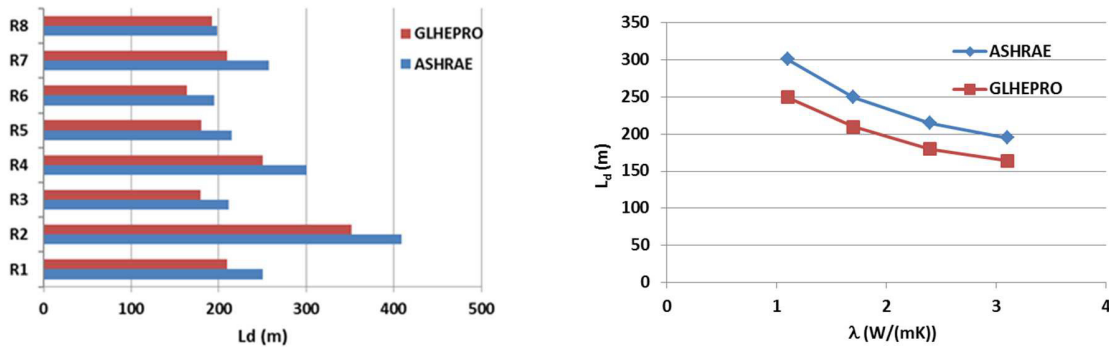


Figure 1. Residential case study: (a) L_d in the different cases for the two methods; (b) L_d versus ground conductivity

3.2. Office case study

The office case study is cooling dominated and thus the resulting design length is the cooling mode one. The main inputs and the sizing outputs in the generated cases are shown in Table 3. In all the cases the double U-pipe configuration was chosen. In order to avoid the influence of a different R_b value on the comparison, the GLHEPRO calculated $R_b = 0.11$ m.K/W was adopted also for ASHRAE.

Table 3. office case: parametric study

Case	λ_g [W/(m.K)]	$T_{f,out}$ [°C] (heating)	$T_{f,out}$ [°C] (cooling)	boreholes distance [m]	BHE layout	ASHRAE/GLHEPRO			L_d difference [%]
						L_d [m]	SCOP	SEER	
O1	1.7	2	32	7	Rectangle (3x5)	1776/1452	2.9/3.9	4.2/5.4	18
O2	1.7	2	30	7	Rectangle (4x4)	2001/1627	2.9/3.9	4.4/5.3	19
O3	1.7	2	35	7	Rectangle (3x4)	1527/1295	2.9/3.9	3.9/5.3	15
O4	1.1	2	32	7	Rectangle (4x5)	2392/1737	2.9/3.9	4.2/5.3	27
O5	2.4	2	32	7	Rectangle (3x4)	1548/1267	2.9/3.9	4.2/5.4	18
O6	3.1	2	32	7	Rectangle (2x5)	1354/1114	2.9/3.9	4.2/5.4	18
O7	1.7	2	32	7	Line (1x15)	1722/1378	2.9/3.9	4.2/5.3	20
O8	1.7	2	32	3	Rectangle (4x5)	2184/1693	3.1/4.0	4.1/5.4	22
O9	1.7	2	32	5	Rectangle (3x5)	1857/1487	2.9/3.9	4.2/5.4	20
O10	1.7	2	32	9	Rectangle (3x5)	1740/1415	2.9/3.9	4.2/5.4	19
O11	1.7	2	32	11	Rectangle (3x5)	1703/1390	2.9/3.9	4.2/5.4	18

In the base case (O1) ASHRAE design length is 18% larger than GLHEPRO. As in the residential case, also in the office case study the BHE size is very sensitive to the fluid temperature at the heat pump outlet (O2 and O3) and to the ground thermal conductivity (O4, O5, O6), whatever the sizing method adopted.

By passing from a rectangular to a linear layout (O7) only 3% and 5% of the BHE total length can be saved, according to ASHRAE and GLHEPRO respectively.

In turn the borehole distance has an important impact on the BHE size (see cases O8-O11). As shown in Figure 2b by decreasing the distance from 7 to 3 m the BHE size increases by 23% and 17% according to ASHRAE and GLHEPRO respectively. In turn increasing the distance to 11 m means saving only 4% of the total length. Therefore an optimal borehole distance can be found of about 7 m.

Also in this medium scale case study ASHRAE sizing tends to be larger than GLHEPRO (see Figure 2a): the difference between the two methods ranges from a minimum of 15% to a maximum of 27%. It can be noticed that the largest disagreement is found in those cases where the thermal perturbation in the ground is expected to be more relevant, either due to low ground conductivity (O4) or to small boreholes distance (O8).

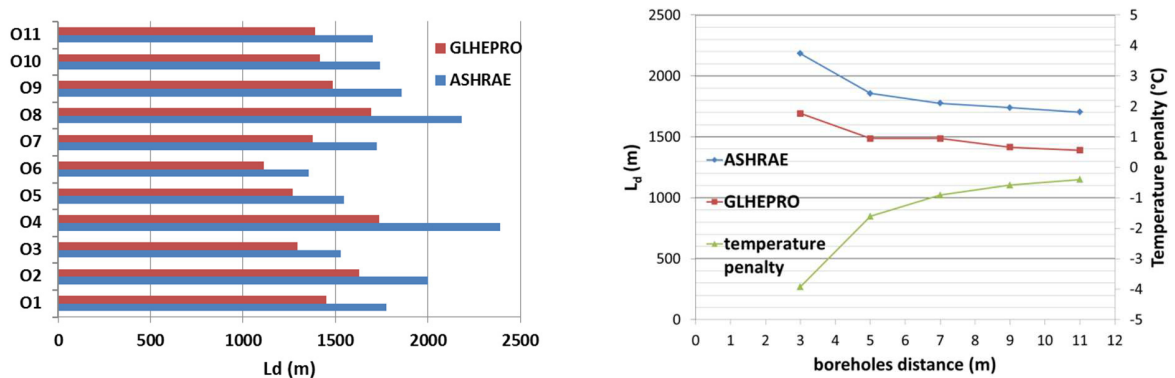


Figure 2. Office case study: (a) L_d in the different cases for the two methods; (b) L_d and temperature penalty vs boreholes distance

4. Conclusions and prospects

The comparison between ASHRAE and GLHEPRO methods shows that ASHRAE sizings are generally larger than GLHEPRO. A possible explanation relates to ASHRAE sizing equations, giving noticeable importance to the peak load conditions. The choice of the design method can impact from a minimum of 14% to a maximum of 27% on the sizing. The comparison has also shown that different borehole thermal resistance calculation methods can result in remarkably different results, influencing the final sizing. Therefore a possible development of this study will investigate R_b calculation approaches.

At the same time the sensitivity analysis has shown that some design choices, regarding the fluid temperature levels on the ground side, and some input uncertainties, related to the ground thermal conductivity, may have an influence on the final sizing of the same order of magnitude of the choice of the sizing method.

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