An improved method for vertical geothermal borefield design using the Temperature Penalty approach

Marco Fossa[1], Davide Rolando[2]

[1] DIME, [2] DIBRIS, University of Genova, via Opera Pia 15a, 16145, Genova, Italy

Email: marco.fossa@unige.it

Keywords: Ground Coupled Heat Pumps, Borehole Heat Exchanger Design, Temperature Penalty.

ABSTRACT

The Ashrae method (Kavanaugh and Rafferty) is one of the few engineering models that allows a system Borehole Heat Exchangers (BHE) to be quickly designed starting from the knowledge of the building thermal energy requirements. The method is based on Infinite Source solutions from ground dynamic response to a series of three heat pulses, representing the building thermal history from the short to the long period. The key parameter of the Ashrae procedure (recently adopted also as an Italian Standard) is the evaluation of the Temperature Penalty correction T_p, which takes into account the thermal interactions of neighbour boreholes in the long term period.

In this paper a new method is addressed to the calculation of the T_p parameter and it refers to a physically based approach of mutual interactions among the BHEs. The improved method has been conceived for maintaining the simplicity of the original Ashrae scheme while enabling a more accurate estimation of the Temperature Penalty values and hence a more reliable BHE field design data. The validation of the proposed procedure and the estimation of the constants involved in the new T_{p8} method is based on the "exact" calculation of the T_p values starting from FLS generated g-functions, able to describe the ground response of a large number of BHE configurations, including square, rectangular, in-line, L-shaped, open rectangles.

It is demonstrated that for the set BHE configurations here considered (about 120) the average deviation of the Ashrae T_p values (with respect to the FLS benchmark) is above 46% with a typical underestimating behaviour which reflects in underestimating the BHE field overall length. On the other hand the proposed method yields T_p percentage deviations well centered around the benchmark line and with an average deviation of 18%. The new method, with respect to benchmark set and in heating mode operations, is able to yield the design BHE length within 5% with respect to the reference solutions.

1. INTRODUCTION

Ground coupled heat pumps (GCHP) are an energy efficient solution for building heating and cooling; Since more than 20 years the technology diffused in northern countries starting from Sweden and the US. Geothermal heat pumps are suitable for covering a wide range of energy demand, from small residences to large commercial buildings, provided that a correctly designed system of ground heat exchangers is coupled to the inverse machine. As it is well known, the most popular solution for extracting/injecting heat to the ground is the closed loop vertical heat exchangers, where a single or double U-pipe is inserted in a drilled borehole. Borehole heat exchangers (BHEs) are hence constituted by polyethylene pipes where the thermal fluid is flowing, the borehole itself and a thermally suitable intermediate medium, that often is a cementitious grout or simply borewater. Pure water or a water glycol solution is finally the typical the heat carrier fluid.

The borefield design problem is to define the best BHE arrangement and the minimum overall length of ground heat exchangers according to the constraints of the problem: building heating/cooling demand, expected heat pump performance (COP and EER as a function of thermal fluid return temperature), ground thermal properties, pipe type and geometry, fluid working conditions and grout properties, land availability for arranging matrixes of boreholes. The problem is made complicated by the transient features of either the building thermal loads or the ground response, the latter being a combination of short and long period response modes. Thermal processes in GCHP applications range from hours to months, due to heat pump working modes, up to years, as a consequence of the long term ground transient response.

In order to simplify the problem to an engineering level, a number of assumptions are made with reference to the heat transfer processes at BHE/ground interface. The main assumptions is to consider pure thermal conduction and constant ground properties. Under those hypotheses, a number of simple solutions of the transient 3D Fourier problem have been proposed in order to describe the ground thermal response to constant heat load released or absorbed at BHE boundary.

The borehole itself can be geometrically simplified by assuming that from a thermal point of view it acts like a linear or cylindrical source, of finite or infinite length. The most popular solutions (Temperature Response Factors, TRF) are those of the so called infinite linear source (ILS) and infinite cylindrical source (ICS). Both methods provide the temperature distribution in the ground as a function of a dimensionless time and along the radius measured from heat source axis. The line source theory (Kelvin, and later by Ingersoll et al., 1954), approximates the BHE as an infinitely long thin line in an infinite medium, while in the cylindrical source method (Carslaw and Jaeger, 1947) a constant heat transfer rate is applied to a cylindrical surface of finite radius and infinite length. It is thanks to Eskilson (1987) and to the Lund University research group if at the end of the 80s, the response factor approach started to be extensively applied to finite length and even multiple heat sources. The Lund group named the new response factors “g-functions” and a great number of BHE geometries have been investigated, by numerically solving the heat conduction equation and by applying proper superposition techniques. In the next two decades from Eskilson contribution, a number of authors successfully applied the response factor approach to more general situations, where in addition to multiple BHE geometries, the heat load profile cannot be considered not constant but constituted by a stepwise function of time. The approach is known as temporal superposition, first suggested by Carslaw and Jaeger and refined by a number of authors, including Eskilson himself, Yavuzturk and Spitler (1999), Bernier et al. (2004).

Another research front on temperature response factors is that addressed to the analytical solution of the Finite Line Source problem (FLS): the main recent contributions are those by Zeng et al. (2004) and Lamarche and Beauchamp (2007) who developed a new expressions for FLS model thus providing new possibilities for spatial superposition and g-function generation for imposed heat flux problems.

The superposition techniques can be applied with any temperature response factor including the ICS solution. Deerman and Kavanaugh (1991) and later Kavanaugh and Rafferty (1997) employed the ICS solution to superpose a series of three heat pulses spanning from hours to a decade. The model by Kavanaugh and Rafferty is known as the ASHRAE method, after being adopted as standard in the Ashrae Handbook (since 2003 on). The Ashrae method has recently become the Italian UNI standard for BHE design (2012).

The strength of the Ashrae method is its substantial simplicity, that allows a fast engineering BHE design without the need of dedicated computer codes, as those based on monthly or hourly description of the building heat load profiles (Hellström and Sanner (2001), Spitler et al. 2009).

The Ashrae method describes the long term thermal history of the building as constituted by three primary pulses (named yearly, monthly and hourly) and adopts the ICS solution to describe the ground response.

As well known, the ICS solution has limitations especially for long term effects (e.g. Philippe et al., 2009): this is the reason why the Ashrae method introduces a correction parameter named “Temperature Penalty” T_p, able to take into account the ground interaction to a complex systems of BHEs, finite in length and in number greater than the unity.

The standard itself does not provide a clear insight on the physical meaning of the Temperature Penalty. Fossa (2011) recently offered a demonstration on T_p genesis and physical meaning. Another contribution on temperature penalty estimation has been offered by Philippe et al. (2010)

In this paper a new method for evaluating the T_p parameter is proposed. The method refers to a physically based approach of mutual interactions among the BHEs. The improved method has been conceived for maintaining the simplicity of the original Ashrae scheme while enabling a more accurate estimation of the Temperature Penalty values. The validation of the proposed method and the estimation of the constants involved in the new method (named T_{p8}) is based on the “exact” calculation of the T_p values starting from FLS generated g-functions, able to describe the ground response for a comprehensive set of BHE configurations, including square, rectangular, in-line, L-shaped and open rectangles.

2. THEORETICAL BACKGROUND

The thermal interaction between the ground and a BHE arrangement, when underground water circulation can be neglected, is governed by the three-dimensional time-dependent conduction equation.

A number of one-dimensional (in the radial direction) and two-dimensional (radial and axial) analytical solutions have been proposed, able to simulate the ground response to a single constant heat pulse. These solutions represent proper temperature response factors. These solutions can be used to obtain the time varying carrier fluid temperature from complex BHE systems for any stepwise function describing the variable thermal load to the ground during the seasons. To this goal, a suitable temporal superposition technique is applied. Furthermore spatial superposition allows the 1D and 2D solutions to be applied to obtain quasi 3D solutions. Three-dimensional temperature response factors (or g-functions) can then be applied for multi-annual simulations, even at hourly time step level.

Analytical approaches can be divided into models based on the line source theory and models based on the cylinder source method. Both methods refer to an homogeneous medium (the ground) and give the radial temperature distribution as a function of time. The line source theory (ILS) approximates the BHE as an infinitely long line in an infinite medium subjected to a constant heat transfer rate per unit length. The cylindrical source method (ICS) is similar to the line source method except that the constant heat transfer rate condition per unit length (Q') is applied to a cylindrical surface of radius r_b. Heat transfer rates Q are usually considered positive if entering the ground control volume (i.e. injected into the soil). The ground temperature excess (at radius r), with respect to far field temperature ($T_{gr,\infty}$), is expressed in the ILS solution as:

$$T(r) - T_{gr,\infty} = \frac{Q'}{4\pi k_{gr}} \int_{1/4Fo_r}^{\infty} \frac{e^{-\beta}}{\beta} d\beta = \frac{Q'}{4\pi k_{gr}} E_1\left(1/4Fo_r \right) \quad [1]$$

where E_1 is the exponential integral, that can be expressed as a series expansion in terms of the ($1/4Fo_r$) variable

According to the ICS model, the temperature excess is on the other hand given in terms of Bessel's functions. Carslaw and Jaeger have also presented an abbreviated expression for this solution, introducing the "G" function:

$$T(r) - T_{gr,\infty} = \frac{Q'}{k_{gr}} G\left(Fo_{rb}, r / r_b\right) \quad [2]$$

where Fo_{rb} is the Fourier number based on BHE radius:

$$Fo_{rb} = \frac{\alpha_{gr}\tau}{r_b^2} \quad [3]$$

and k_{gr} and α_{gr} are the ground thermal conductivity and thermal diffusivity, respectively. Tabulated values and also correlations are available for evaluating the G values as a function of Fo and dimensionless radius.

A new insight to the linear source theory was given by the finite linear source model (FLS). This evolution of the ILS problem took great advantage from the Lamarche and Beauchamp expressions, which provide the averaged (along the depth H) borehole temperature in terms of the complementary error function (erfc) according to the formulas:

$$T_{ave}(r) - T_{gr,\infty} = \frac{Q'}{2\pi k_{gr}} \left[\int_{\beta}^{\sqrt{\beta^2+1}} \frac{erfc(\gamma_F z)}{\sqrt{z^2-\beta^2}} dz - D_A - \int_{\sqrt{\beta^2+1}}^{\sqrt{\beta^2+4}} \frac{erfc(\gamma_F z)}{\sqrt{z^2-\beta^2}} dz - D_B \right] \quad [4]$$

where $\beta = r/H$, $\gamma_F = 0.5(Fo_H)^{0.5}$.

In Eq. [4], DA and DB are also expressed as a function of erfc, and they are constants at given time and depth H.

By exploiting the linear properties of the conduction equation and by applying the spatial superposition of solutions it is possible to evaluate the ground response to a system of BHEs. The spatial superposition can be applied to calculate the response of a BHE field to a heat step pulse, resulting in a mean borehole wall temperature for the whole borefield: this is the way for calculating the g-function of that BHE geometry.

Therefore, the thermal response of a given borefield (B is the BHE spacing and r_b the BHE radius) can be expressed as:

$$T_{ave}(r_b) - T_{gr,\infty} = \frac{Q'_{ave}}{2\pi k_{gr}} g\left(\ln(9Fo_H), r_b/H, B/H, borefield\,geometry\right) \quad [5]$$

where Fo_H is the H based Fourier number, $T_{ave}(r_b)$ is the average borehole wall temperature for the whole borefield, and Q'_{ave} is the average heat transfer rate per unit length in the whole borefield. Cauret and Bernier (2009) and Fossa (2011b), confirmed the possibility to generate g-functions based on the FLS solution, but as already stressed by Lamarche and Beauchamp, some variances (up to 10%) exist among published Eskilson g-function values and those evaluated by the FLS superposition.

Temperature response factors (including the g-functions) can be employed for temporal superposition. The Kavanaugh and Rafferty procedure (also known as the Ashrae method) can be ascribed to the temporal superposition techniques.

Without retracing the theory and hypotheses behind (the reader is addressed to Fossa 2011), the final Ashrae formula for BHE field design can be written according to the following expression:

$$L = \frac{\left\{Q_y R_y + Q_m R_m + Q_h \left(R_h + R_{bhe}\right)\right\}}{T_{gr,\infty} - T_{f,ave}(\tau_N) - T_p} \quad [6]$$

where L is the overall length of BHEs, R_y, R_m, R_h are ground thermal resistances calculated according to the ICS model, the Q terms are the average heat transfer rates at the ground on a multiyear time scale (10 year average), a monthly time scale (1 month, the "most demanding" of the year) and a hourly time scale (6 hours, the peak load). $T_{f,ave}$ is the expected (for expected COP) carrier fluid temperature at the end of the operating period τ_N (10 years, plus 1 month, plus 6 hours).

R_{bhe} is finally the time invariant thermal resistance of the BHE, that can be estimated for from a thermal response test or suitable formulas (e.g. Zeng et al., 2003).

The T_p term is the temperature penalty is introduced in the Ashrae standard as the "penalty for interference of adjacent bores", without any other explication.

On the other hand it can be demonstrated that the T_p term is related to the error introduced by the G solution with respect to the "true" one, say the proper g-function for the borefield under consideration (Fossa, 2011).

$$T_p(L) = \frac{Q_y\left(g/2\pi - G\right)}{Lk_{gr}} \quad [7]$$

where both the g or its "big brother" G are calculated at Fo corresponding to τ_N.

Equation (7) states a number of interesting things: a) the correct design of the borefield is strictly linked to a reliable estimation of T_p since the method is implicit with respect to L; b) the correct T_p evaluation should be based on some g-function approach, c) T_p can be different from zero even for the single borehole, provided that the yearly (net) load Q_y is itself different from zero.

3 METHODS FOR ESTIMATING THE TEMPERATURE PENALTY

In this paragraph methods for calculating the T_p term are presented, with particular attention to the original Ashrae method and to the new proposed one. Discussions and comparisons with respect to the Philippe et al. method (2010) will be tackled in a future paper. As a preliminary comment, the proposed method to Authors' opinion offers a better accuracy than the Philippe one while having major advantages in terms of simplicity and no limitation on BHE field geometry.

3.1 The Ashrae approach to the Temperature Penalty calculation

The Ashrae method (and its UNI Italian counterpart, 2012) suggests to calculate the temperature penalty term through a series of formulas, which are those proposed by Kavanaugh and Rafferty (1997). The core of the calculation is the evaluation of the "heat diffused inside a square cylinder" according to an expression containing the "temperature change in the local earth surrounding the bore", T_{p1}. The related expression can be recast in the following way:

$$T_{p1} = \frac{Q_y \sum_{i=1}^{n} (R_{i+1}^2 - R_i^2) E_{1,i}(\tau_N, \frac{R_{i+1} + R_i}{2})}{4k_{gr}LB^2} \quad [8]$$

Here the i-th radius R_i is representative of a shell around the borehole, R_1 is equal to B/2, R_n is the "maximum radius", indicatively around 25-30 feet (but not related to B).

T_p according to Ashrae (T_{pA} hereafter) is finally expresses as:

$$T_{pA} = T_{p1} \frac{N_4 + 0.5N_3 + 0.25N_2 + 0.1N_1}{N_{tot}} \quad [9]$$

where N_4, N_3, N_2 and N_1 are the number of boreholes surrounded by "only" 4 other ones, only 3 other ones, and so on, respectively. In order to explain the criterion, a rectangular borefield constituted by 3x4 BHEs has N_4=2, N_3=6, N_2=4, N_1=0, N_{tot}=12.

3.2 The proposed Tp8 method as an improved Temperature Penalty estimator

The proposed method is based on the assumption that the T_p term has to be expressed in some similar wau to a g-function. Since g-functions can be effectively calculated by superposing in space the FLS solution a similar approach is adopted here, but the ILS solution is adopted for the sake of simplicity.

The reference geometrical condition is the one where a single BHE is surrounded by other 8, arranged in a regular matrix where the BHE pitch is B. Four BHEs are a B distance apart from the central one while the other 4 are √2B far from the pivot. The principles of spatial superposition state that the excess temperature θ_{p8} at the central BHE, in a ILS scheme and referring to a Q_y thermal power, is given as:

$$\theta_8 = Q_y \frac{E_1(\tau_N, B) + E_1(\tau_N, B\sqrt{2})}{\pi k_{gr} L} \quad [10]$$

The T_p according to the present model (hereafter T_{p8}) is finally expressed in a form which deliberately resembles the original Ashrae one.

$$T_{p8} = \theta_8 \frac{aN_4 + bN_3 + cN_2 + dN_1}{N_{tot}} C_N(N_{tot}, B/H) \quad [11]$$

Constant (a, b, c, d) derivation, correction term C_N and model validation is discussed in the following paragraph.

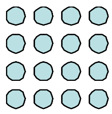
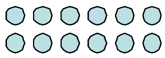
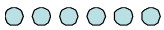
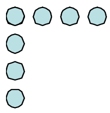
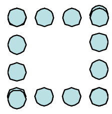
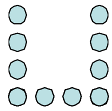
4. BHE CONFIGURATIONS FOR METHOD REFINEMENT AND VALIDATION

In order to calculate the proper constants to be applied in Eq. [11] and to estimate the proposed model uncertainty with respect to the adopted reference solutions, a huge number of BHE configurations have been considered and related g-functions calculated with FLS spatial superposition, as done for example in Fossa (2011, 2011b). The borefields taken into account (see Table 1) include square configurations (up to 10x10 BHEs), rectangular (up to 10x8), in-line (up to 12x1), L configurations (up to 10x10L), U configurations (up to 10x10U) and open rectangles (O configurations, up to 12x12O). The calculations were performed for B/H equal to 0.03, 0.05 and 0.1 in the range of practical interest of Fourier numbers with respect to time τ_N.

The number of cases M here considered were about 35 for optimum search; the corresponding cases M_2 for validation and comparisons were about 120.

The g-function set built in the above way was hence employed to calculate the "true" T_{pg} values according to Eq. [7] and to refine the T_{p8} formula in terms of its

Table 1: BHE configuration set for model validation and method comparisons.

BHE arrangements	Square configurations	Rectangular	In Line	L shaped	O shaped	U shaped
	2x2	3x2	2x1	2x2L		
	3x3	4x2	3x1	3x3L	3x3O	3x3U
	4x4	6x3	4x1	4x4L		
	5x5	6x4	5x1	5x5L		
	6x6	8x2	6x1	6x6L		
	7x7	8x4	7x1	7x7L		
	8x8	8x6	8x1	8x8L		
	9x9	9x4	9x1	9x9L		
	10x10	9x6	10x1	10x10L	10x10O	10x10U
		9x8	12x1		12x12O	
		10x6				
		10x8				
B/H=0.03, 0.05, 0.1 rb/H=0.0005						

constants a, b, c, d. The optimum analysis was aimed at minimizing the average of the absolute values of percentage error (T_{p8} estimates vs g-function T_p "true" values, Eq. [7]). The objective function F to be minimized is hence given by the expression:

$$F(a,b,c,d) = \frac{1}{M}\sum_{j=1}^{M}\left|T_{p,j} - T_{p8,j}\right| \quad [12]$$

In order to make more clear the comparison and the errors introduced by the standard Ashrae procedure in evaluating the overall BHE length, together with the temperature penalty values a required (design) length have been calculated for each BHE configuration temperature penalty model. To this aim a reference heat load profile to the ground was defined. This profile is arbitrary, but reasonably able to describe typical monthly variations in heat demand to the soil.

This heat load profile is depicted in Figure 1 and it compares well with the 10x10 configuration. Figure 1 shows the (monthly) average heat transfer rates extracted from the ground as they varies along the year. The yearly average is also depicted together with the hourly (peak) extraction value, here calculated as 2.6 times the January value which in turn represents the monthly value Q_m to be employed in Eq. [6]. Worth noticing, no building cooling mode is here considered (unbalanced yearly load), in order to emphasize the T_p influence on borefield design results.

The reference heat load profile (Figure 1) was scaled "in intensity" by a constant value to cope with different BHE geometries. The scaling factor, applied to all monthly values, is roughly proportional to N_{tot}, even if a more fine (trial and error) criterion was applied, which for the sake of brevity is not described here. In such a way the "shape" of the heat load profile was preserved while just reducing each monthly contribution of the same percentage amount. For BHE overall length L calculation, the results refer to ground conductivity and diffusivity values equal to 2.7 and 1.62E-6 respectively, in SI units. To finalize the calculation of L according to Eq. [6], the difference ($T_{gr,\infty}$-$T_f(\tau_N)$) is set to 12°C.

4. RESULTS AND DISCUSSION

An optimum search have been applied to minimize the objective function F defined in Eq. [12] in terms of the best constants a, b, c, d. Again, for the sake of brevity this part is not described here. The optimum search was performed for a subset of the BHE configurations listed in Table (1). The choice of this subset of 35 configurations was arbitrarily done in order to quite uniformly span on overall Lengths L, from few hundreds meters to about 10^4 m (N_{tot} from 2 to 100), with a predominance of rectangular and square configurations. The optimum constants have been calculated for the cases B/H=0.03, 0.05 and 0.1. The results showed that constants did not change significantly for the cases B/H=0.03 and B/H=0.05. These constants are reported in Table (2).

Table 2: Constants for Tp8 calculation according to formula [11], for B/H=0.03, 0.05

a	b	c	d
3.82	0.34	0.50	0.10

To correctly evaluate the T_{p8} values in case of larger separating distances (say B/H=0.10), a correction term C_N was introduced (see Eq. [11]). The correction to be applied was found to be dependent on the overall BHE number N_{tot}.and it was expressed as:

$$C_N(N_{tot}, B/H) = \begin{cases} 1 & for\ B/H = 0.03, 0.05 \\ 0.864 N_{tot}^{0.215} & for\ B/H = 0.10 \quad (2 < N_{tot} < 100) \end{cases}$$

[13]

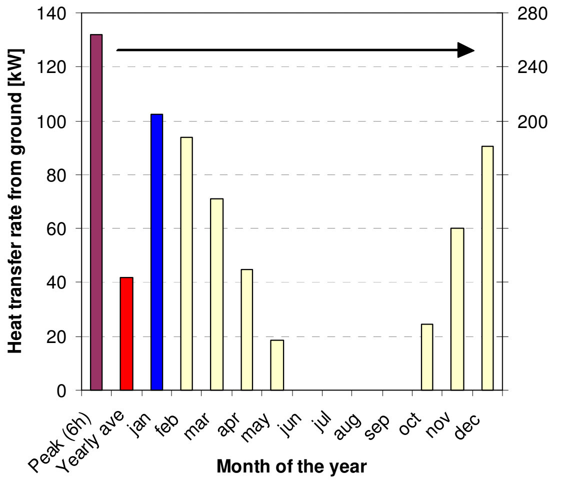


Figure 1: Base heat load profile to the ground for BHE overall length L design.

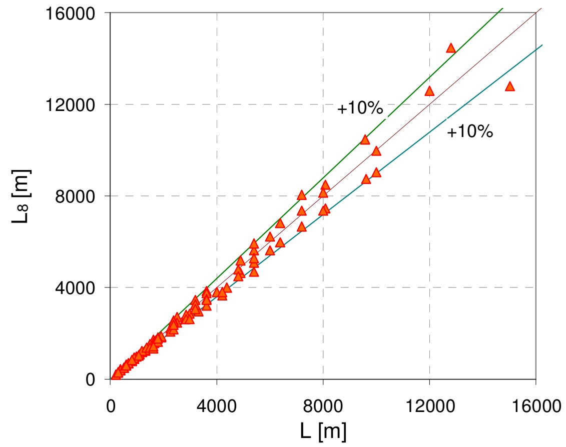


Figure 2: Calculated overall length L according to the reference T_p model and the proposed T_{p8} one. 121 BHE configurations.

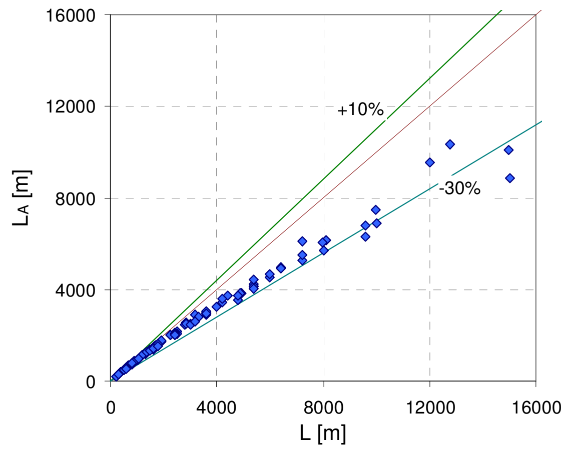


Figure 3: Calculated overall length L according to the reference Tp model and the Ashrae TpA one. 121 BHE configurations.

The comparisons and the related validation of the present model have been made with reference to the whole set of BHE configurations, constituted by more than 120 different geometrical arrangements, with B/H ranging from 0.03 to 0.10. The BHE depth was set for most configurations equal to 100 m, but for few borefields H was set to 150 and 200 meters, in order to also take into account the influence of different Fo_H numbers on the g-function values.

Figure 2 shows the calculated BHE overall length for the whole M_2 set of configurations according to either the "true" T_p values (L) or to the proposed T_{p8} ones (L_8). In this Figure, and in the following ones, the highest lengths correspond to larger BHE fields, in terms of BHE number. With some 0.5% accuracy L resulted (due to heat load profile tuning) H times N_{tot}, in meters, where H was set for most cases equal to 100 m.

As can be observed the design of the BHE field according to the proposed model is in good agreement with the reference g-function values. A closer inspection of data plotted in Figure 2 would reveal that the average percentage difference between L_g and L_8 is 4.4%. The best estimates given by the T_{p8} method are those related to the large configurations, either for the closed or open arrangements, where the agreement is within 2.5%.

Finally it can be observed that the majority of L_8 points are within the ±10% boundaries, say they are characterised by the same uncertainty that typically pertains to the ground conductivity values.

Figure 3 is the counterpart of Figure 2: the length L_A (say evaluated according to the T_{pA} model) is plotted against the corresponding lengths L. The Figure makes apparent as the Ashrae approach (T_{pA} formulas) can yield to important errors in the BHE design process, especially with respect to large BHE fields. The average percentage difference between L and L_A is 12%, but for large matrix configurations (rectangular and square configurations, 6 BHE or more per side) the average difference is 22%. In addition the average percentage error is increasing with BHE number in the direction of an underestimation of the required length.

As an example, a heat load profile requiring some 10x10 configuration, would be characterised by an overall length L_A equal to 6900 meters, while the "exact" estimation according to the T_p formula [7] is 10000 meters, some 44% more.

Figures 4 and 5 report the same results of Figures 2 and 3 but in term of the T_p, T_{p8} and T_{pA} values. In this sense the comparison can show with a greater detail the capability of each model to cope with the FLS g-function model.

Figure 4 represents the comparison between T_p and T_{p8}. It can be observed that data are spread around the bisector line: the slope coefficient of the linear regression resulted 0.97. The average percentage difference is 17% and the standard error of estimates of T_{p8} values (with respect to T_p ones) is 0.51 C°. The higher discrepancies in the temperature penalty estimation according to the present model pertain to small installations, with few BHEs, with no particular influence of the configuration type.

The corresponding representation of T_{pA} vs T_p values (Figure 5) shows a tendency of the Ashrae approach to underestimate the reference values, typically of some 40-50% (slope of the regression line is 0.57), with maximum (negative) discrepancies up to 65%.

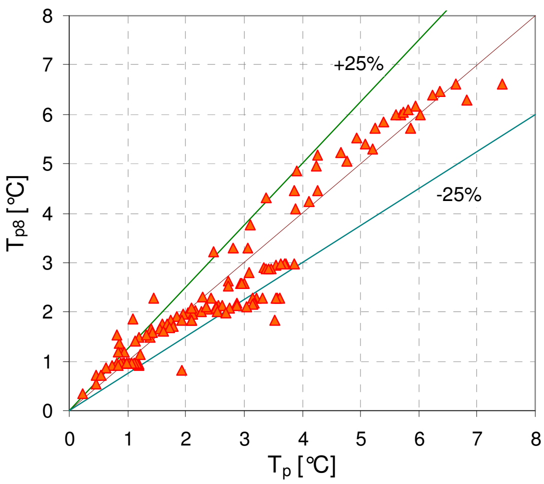


Figure 4: Calculated reference Tp values vs Tp8 ones (present model).

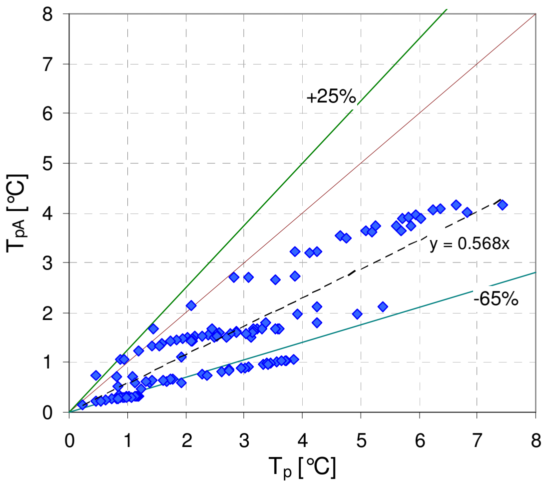


Figure 5: Calculated reference Tp values vs TpA ones (Ashrae method).

5. CONCLUSIONS

In this paper a new method has been proposed for a reliable calculation of the Temperature Penalty correction term introduced in the Ashrae standard for BHE field design. The improved method has been conceived for maintaining the simplicity of the original Ashrae scheme while enabling a more accurate estimation of the T_p values and related BHE overall lengths. The refinement and validation of the proposed method was based on the "exact" calculation of the T_p values starting from FLS generated g-functions. The overall number of BHE configurations was about 120, including square, rectangular, in-line, L-shaped, U and O-shaped arrangements.

It has been demonstrated that for the present set of BHE geometries the average deviation of the Ashrae T_{pA} values (with respect to the FLS benchmark) is above 46% with a typical underestimating behaviour which reflects in calculating reduced BHE overall lengths (undersizing of BHE field). In addition this underestimation is increasing with borefield extension (or BHE number). The proposed method on the other hand yields temperature penalty percentage deviations well centered around the benchmark line and with an average deviation of 18%. This error is even lower at high T_p values (large BHE fields) and it yields to BHE overall length estimates in good agreement (average difference less than 5%) with the reference method.

Future work on this subject could include the calculation of T_{p8} constants based on B/H values (and eventually for configuration type), a comparison with other temperature penalty estimating methods, a critical review of reference g-functions sets.

REFERENCES

ASHRAE handbook-HVAC Applications, Chapter 32, Geothermal Energy, (2003)

Bernier, M.A., Pinel, P., Labib, R., Paillot, R.: A Multiple Load Aggregation Algorithm for Annual Hourly Simulations of GCHP Systems, *Ashrae Hvac & Res. J.*, 10, (2004), 471-488.

Carslaw, H.S. and Jaeger, J.C.: Conduction of Heat in Solids, *Claremore Press,* Oxford, U.K., (1947).

Cauret, O., Bernier, M.A: Experimental Validation of an Underground Compact Collector Model, *Proc. 11th Int.Conf. Effstock Stockholm*, (2009).

Deerman, J.D., Kavanaugh, S.P.: Simulation of Vertical U-tube Ground Coupled Heat Pump Systems using the Cylindrical Heat Source Solution, *ASHRAE Transactions*, 97, (1991), 287-295.

Eskilson, P.: Thermal Analysis of Heat Extraction Boreholes. Ph.D. Thesis, *Lund University of Technology*, Sweden, (1987).

Fossa, M.: the Temperature Penalty Approach to the Design of Borehole Heat Exchangers for Heat Pump Applications, *Energy and Buildings*, 43, (2011), 1473-1479.

Fossa M.: A Fast Method for Evaluating the Performance of Complex Arrangements of Borehole Heat Exchangers , *Ashrae Hvac & Res. J.*, 17, (2011b), 948-958

Ingersoll, L.R., Zobel, O.J., and Ingersoll, A.C.: Heat Conduction with Engineering, Geological, and other Applications, *McGraw-Hill,* New York, (1954).

Hellström, G. and Sanner, B.: PC-Programs and Modeling for Borehole Heat Exchanger Design, *Proc. IGD 2001 Bad Urach*, Supplement, ISS Skopje, (2001).

Kavanaugh, S.P. and Rafferty, K.: Ground Source Heat Pumps Design of Geothermal System for Commercial and Institutional Buildings. *ASHRAE Conf.*, Atlanta, (1997).

Lamarche, L. and Beauchamp, B.: A New Contribution to the Finite Line-Source Model for Geothermal Boreholes, *Energy and Buildings*, 39, (2007), 188-198.

Spitler, J.D., Cullin, J., Bernier, M.A, Kummert, M., Cui, P., Liu, X., Lee, E., Fisher, D.: Preliminary intermodel comparison of ground heat exchanger simulation models. *Proc. 11th Int.Conf. Effstock* Stockholm, (2009).

Philippe, M., Bernier, M., Marchio, D.: Validity ranges of three analytical solutions to heat transfer in the vicinity of single boreholes, *Geothermics*, 38 (2009) 407-413.

Philippe, M., Bernier, M.A., Marchio, D.: Sizing Calculation Spreadsheet for Vertical Geothermal Borefields, *Ashrae J.*, (2010), 20-28

UNI Italian Standard 11466:2012: Sistemi geotermici a pompa di calore - Requisiti per il dimensionamento e la progettazione, (2012).

Yavuzturk, C. and Spitler, J.D.: A Short Time Step Response Factor Model for Vertical Ground Loop Heat Exchangers, *ASHRAE Transactions*, 105, (1999), 475-485.

Zeng, H.Y., Diao, N.R., Fang, Z.H.: A Finite Line-Source Model for Boreholes in Geothermal Heat Exchangers, *Heat Transfer-Asian Research*, 31, (2002), 558-567.

Zeng, H., Diao, N., Fang, Z.: Heat Transfer Analysis of Boreholes in Vertical Ground Heat Exchangers. *Int, J. Heat and Mass Transfer*,46 (2003), 4467–4481.