IMPROVING THE ASHRAE METHOD FOR VERTICAL GEOTHERMAL BOREFIELD DESIGN

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Abstract: The design of a system of Borehole Heat Exchangers (BHE) coupled to a geothermal heat pumps have to be done with a suitable dynamic model able to cope with the intrinsic time varying behaviour of the ground mass and building heat load profile. Among the models based on the solution of transient conduction equation, the Ashrae method (Kavanaugh and Rafferty) is probably the fastest algorithm for calculating the overall length of ground heat exchangers starting from the knowledge of the building thermal energy requirements and ground properties. This method employs Infinite Source (IS) solutions for describing the ground response to a series of three heat pulses, representing the building thermal history from the short to the long period. Since IS solutions cannot describe 2D and 3D effects in the ground temperature field, a correction parameter is introduced. This parameter is named Temperature Penalty T_p, which also accounts for the thermal interactions of neighbouring boreholes in the long term period.

In this paper a new method is proposed for the calculation of the T_p parameter. The new method is conceived for maintaining the simplicity of the original Ashrae model while enabling a more accurate design of the BHE field. The validation of the proposed procedure and the estimation of the constants related to the new method is made by assuming the T_p values as inferred from FLS generated g-functions, able to describe the ground response to a large number of BHE configurations, including square, rectangular, in-line, L-shaped, open rectangles. With reference to the present set of BHE configurations (240), it is demonstrated that the Ashrae T_p values are typically underestimating the “correct” value counterparts (average deviation more than 40%), thus leading to an underestimation of the BHE field overall extension. The proposed method, based on the calculation of a set of constants to be applied to specific geometries (square, rectangular, in line arrangements) is able to provide T_p values well centered around the benchmark line and with an average deviation of less than 10%, with estimated BHE overall lengths (ground heat extraction mode) very close (1.4%) to reference FLS values.

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

1 INTRODUCTION

As it is well known, ground coupled heat pumps (GCHP) are probably the most energy efficient solution for building space conditioning, especially in heating mode. This technology has encountered a wide diffusion in northern countries, either in Europe or America. GCHP can cover a wide range of energy demand situations, from small residences to large commercial buildings while yielding high efficiencies (instantaneous COPs and average SPF) in energy conversion with respect to conventional air source heat pumps. To attain such performance the correct design of the ground side of the plant is even more important than the correct selection of the thermal machine or the proper choice of the heat distribution and heat recovery in the building. As it is well known, the most popular solution for extracting/injecting heat to the ground is a closed loop of vertical heat exchangers made by a single or double U-pipe which is inserted in a drilled borehole. Borehole heat exchangers

(BHEs) are usually preferred to horizontal or near horizontal (e.g. trench pipes, coil pipes, pipe baskets) arrangements due a number of reasons, including: the reduced requirement of land surface, the availability of reliable drilling equipment, the stable and (even increasing with depth) ground temperatures, a consolidated history of models and calculation tools for BHE design. The borefield design goal can be summarized in the definition of the best BHE geometry (with respect to land availability and drilling/connection strategies) and the minimum overall length of vertical pipes. The constraints of the problem and its input information are the building thermal energy demand, the ground thermal properties and a target heat pump performance behaviour, in terms of COP, EER or SPF depending on the case. The BHE design problem is intrinsically related to the transient behaviour of either the building thermal profile in time or the ground response, the latter being a combination of short and long period response modes. A number of assumptions are usually made while tackling the BHE design process, the most important one being to consider pure thermal conduction and constant ground properties. Under those hypotheses, a number of simple solutions of the transient Fourier problem have been proposed in order to evaluate the ground temperature field when a constant heat flux condition is imposed at BHE boundary.
The borehole itself is usually modelled as a linear or cylindrical source, of finite or infinite length. The most popular solutions for such a problem are the so called infinite linear source (ILS, Kelvin, and later by Ingersoll et al., 1954) and infinite cylindrical source (ICS, Carslaw and Jaeger, 1947). Both solutions (Temperature Response Factors, TRF) allow the temperature distribution in the ground to be evaluated in terms of a dimensionless time and distance (radius) from heat source axis. The two solutions can be proved to be in absolute agreement except for the very early times, as also discussed in recent papers (Philippe et al. 2009, Lamarche 2010) The ILS model first proposed by Lord Kelvin, and later by Ingersoll et al. (1954), can approximate the BHE heat source as an infinitely long line, buried in an infinite ground. In the ICS description (Carslaw and Jaeger, 1947) a constant heat transfer rate is applied to a cylindrical surface of finite radius and infinite length. Thanks to the work of the Lund research group (e.g. Eskilson, 1987), the TRF approach was extended to the description of complex BHE systems, constituted by finite heat sources arranged in regular arrangements. The Lund approach was based on the numerical solution of the single (finite) heat source problem and on proper superposition techniques in space. Finite Line Source problem (FLS) was also analytically investigated in recent studies, the most important ones being those by Zeng et al. (2004), Lamarche and Beauchamp (2007) and Javed and Claesson (2011).

Temporal superposition is the next step for refining the BHE response analysis. Superposition of basic solutions in time, as first suggested by Carslaw and Jaeger, allows heat transfer rate variations to be accounted for. This technique was successfully applied by several authors, including Eskilson himself, Yavuzturk and Spitler (1999), Bernier et al. (2004).

The superposition techniques (in time but also in space) can be applied to any temperature response factor including the ICS and ILS solutions. Deerman and Kavanaugh (1991) and later Kavanaugh and Rafferty (1997) employed the ICS solution to superpose in time a series of three heat pulses of different duration, from hours to a decade. The model by Kavanaugh and Rafferty, also known as the ASHRAE method (Ashrae Handbook, 2003) was recently adopted as standard for BHE field design in Italy (UNI standard, 2012).

The strength of the Ashrae method is its simplicity: design of the BHE field, in terms of overall BHE length, can be easily performed without dedicated computer as those based on monthly or hourly description of the building heat load profiles (Hellström and Sanner, 2001, Spitler et al. 2009).

As it is well known, the Ashrae method describes the short to long term thermal history of the building with respect to the ground as constituted by three primary pulses, named yearly, monthly and hourly loads. The ICS solution is adopted to describe the corresponding ground thermal resistances and the ILS solution is applied to evaluate the ICS correction term.

The ICS solution, as discussed for example by Philippe et al. (2009), has intrinsic limitations in describing the ground response to multiple BHEs in the long period. For this reason the Ashrae method introduces a correction parameter named “Temperature Penalty” T_p, in order to take into account the mutual interactions among ground heat exchangers.

The standard does not explain clearly the genesis and the physical meaning of this additional parameter. According to the analysis of one the Author of the present paper, (Fossa, 2011) the T_p is proportional to the difference between the ILS solution value and the corresponding g-function one. Another problem is the T_p estimation: a comprehensive method has been recently offered by Philippe et al. (2010)

The present paper is addressed to the evaluation of the T_p parameter as well, according to a formalism that deliberately resembles the original Ashrae one and to a procedure based on a reduced set of constants. The present paper represents an evolution of what recently proposed by the Authors (Fossa and Rolando, 2013). The method applies a spatial superposition scheme in order to describe the mutual interaction among BHEs according to a physical based approach. The new method demonstrated to be able to provide more accurate predictions of the temperature penalty values and overall BHE lengths with respect to the original Ashrae procedure. The validation of the proposed method and the estimation of the constants that are part of it are based on the “exact” calculation of the T_p values starting from FLS generated g-functions. The validation of the model has been carried out for a large number of BHE configurations, including square, rectangular, in-line, L-shaped, U-shaped and open rectangles and constants have been optimized for BHE configuration families.

2 THEORETHICAL 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 the TRF related to the heat source geometry under consideration. Spatial superposition allows the 1D and 2D solutions (i.e. FLS solutions) to be employed for obtaining TRFs able to describe the 3D thermal field of multiple BHE fields. All these TRFs can be used to calculate the ground thermal resistance and then to obtain the time varying carrier fluid temperature, as a function of an additional resistance, know as the borehole resistance. The response of the ground/BHE system to any stepwise function describing a transient thermal load can be evaluated by applying a suitable temporal superposition technique. 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 a dimensionless 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 (ICS) is similar to the line source except that the constant heat transfer rate condition per unit length ($\dot{Q}'$) is applied to a cylindrical surface of radius r_b. Heat transfer rates $\dot{Q}$ 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:

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

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

According to Carslaw and Jaeger, the ICS solution can be written in terms of Bessel's functions; they proposed an abbreviated name for this solution, which is referred as the "G" function:

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

In this case again, the ground temperature excess can be evaluated as a function of the dimensionless time Fo_{rb} , which represents the Fourier number based on BHE radius r_b:

$$Fo_{rb} = \frac{\alpha_{gr}\tau}{r_b^2} \tag{3}$$

Tabulated values and even correlations are available for evaluating the G values as a function of Fo and dimensionless radius.

In the above equations, .k_{gr} and α_{gr} are the ground thermal conductivity and thermal diffusivity, respectively.

A significant contribution to the solution of the single heat source problem is offered by the finite line source (FLS) theory. 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:

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

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

In Eq. (4), D_A and D_B are also expressed as a function of erfc, and they are constants at given time and depth H.

As it is known, the linear properties of the conduction equation allows the spatial superposition technique to be applied to any TRF solution, including the FLS one. In such a way multiple BHE TRFs can be generated: these new solutions are those named g-functions, that can be applied to calculate the thermal response of a BHE field to a continuous heat load, in terms of the mean borehole wall temperature for the whole borefield

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

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

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. Lamarche and Beauchamp (2007) first demonstrated the possibility to successfully employ the FLS solution to infer by superposition any g-function. They also noticed, as done for example also by Cauret and Bernier (2009) and Fossa (2011b), some discrepancies (up to 10%) exist among published Eskilson g-function values and those evaluated by the FLS superposition. On the other hand, at the Fourier numbers pertinent to the Ashrae method horizons, FLS generated g-functions still agree with other literature data sets, as also recently confirmed by Monzo et al. (2013).

Any temperature response factor can be employed for temporal superposition. The Kavanaugh and Rafferty method (here after simply the Ashrae method) can be ascribed to the temporal superposition techniques.
The final Ashrae formula for BHE field design can be written according to the following expression:

$$L = \frac{\left\{ \dot{Q}'_y R_y + \dot{Q}'_m R_m + \dot{Q}'_h \left(R_h + R_{bhe}\right) \right\}}{T_{gr,\infty} - T_{f,ave}(\tau_N) - T_p} \quad (6)$$

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 $\dot{Q}$ 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). In the above equation, the heat transfer rate sign is the one related to the building: in winter mode thermal energy from the heating system is entering into the building (hence positive according to Thermodynamics): the corresponding quantity extracted from ground (weighted through the ratio (COP-1)/COP for the winter mode) is again referred as positive.

R_{bhe} is finally the time invariant thermal resistance of the BHE, that can be estimated for measurements, numerical calculations devoted to the steady state conduction equation solution or from a suitable analytical formulas (e.g. Zeng et al., 2003).

The T_p term is referred 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.

$$T_p(L) = \frac{\dot{Q}'_y \left(g/2\pi - G\right)}{L k_{gr}} \quad (7)$$

where both the g and G temperature factors are calculated at Fo corresponding to τ_N.

The reader is addressed to the work of Fossa (2011), for a detailed derivation of either the T_p expression (equation 7) or the Ashrae superposition that yields the equation (6).
Equations (6) and (7) reveal some interesting features on T_p. First of all the correct design of the borefield is strictly linked to a reliable estimation of T_p since the equation set is implicit with respect to L. Secondly T_p estimates should be based on some g-function approach, as done by Philippe et al. Last consideration, T_p can be different from zero even for the single borehole: for any positive value of the yearly (net) load Q_y (energy is globally extracted from the ground) the penalty term assumes negative values, since the difference (g/2π-G) is typically negative.

3 THE EVALUATION OF TEMPERATURE PENALTY

In this paragraph particular attention is devoted to the comparison of the original Ashrae method results in terms of T_p with respect to the ones that the proposed procedure is able to offer. No comparison is made here with respect to the Philippe et al. method (2010), with respect to which the present approach assures similar accuracy while having some 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 suggests to calculate the temperature penalty term through a series of formulas, which are the original ones by Kavanaugh and Rafferty. The model is centered around the concept 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:

$$T_{p1} = \frac{\dot{Q}'_y \sum_{i=1}^{n} (R_{i+1}^2 - R_i^2) E_{1,i}(\tau_N, \frac{R_{i+1}+R_i}{2})}{4 k_{gr} L B^2} \tag{8}$$

Here the i-th radius R_i is representative of a cylindrical shell around the borehole, R_1 is equal to half of the BHE interdistance (B/2), R_n is the "maximum radius", indicatively around 25-30 feet.

Some criticisms can arise: a square volume is considered but it is made by concentric hollow cylinders, the radial step for summation is nor suggested or related to the interdistance B, the maximum radius itself is not related to B, the ILS solution is here preferred to the G one.
T_p according to Ashrae (hereafter T_{pA}) is finally expressed as:

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

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. As an example for clarifying 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, while an in-line configuration 4x1 has N_4=0, N_3=0, N_2=2, N_1=2.

3.2 The proposed Temperature Penalty method (Tp8 method)

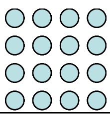
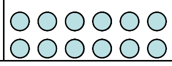
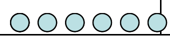
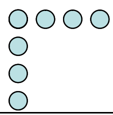
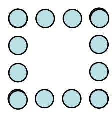
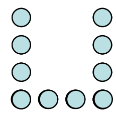
The proposed method is based on the assumption that the T_p term has to be calculated in some similar way according to which the g-functions have been built, say by spatial superposition of single BHE solutions. The present proposal follows the same criterion but the ILS solution is adopted for the sake of calculation simplicity.

The reference geometry is a regular matrix with a single BHE surrounded by other 8. The borefield pitch is B in either the x or y directions. Four BHEs lay at a B distance from the central one while the other 4 are √2B apart from it. The principles of spatial superposition allow the excess temperature θ_{p8} at the central BHE to be evaluated according to the ILS assumption and referring to a $\dot{Q}_y$ thermal power.

$$\theta_8 = \dot{Q}'_y \frac{E_1(\tau_N, B) + E_1(\tau_N, B\sqrt{2})}{\pi k_{gr} L} \tag{10}$$

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

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

BHE arrangements	Square	Rectangular	In Line	L shaped	O shaped	U shaped
	3x3	3x2	3x1	2x2L	3x3O	3x3U
	4x4	6x4	4x1	4x4L	4x4O	4x4U
	6x6	8x6	5x1	6x6L	5x5O	5x5U
	8x8	9x4	6x1	8x4L	6x6O	6x6U
	9x9	9x6	7x1	8x8L	7x7O	7x7U
	10x10	10x2	8x1	10x4L	8x8O	8x8U
	9x9(H=150m)	10x6	9x1	10x6L	9x9O	9x9U
	8x8(H=150m)	10x8	10x1	10x10L	10x10O	10x10U
B/H=0.03, 0.05, 0.075, 0.1, 0.125 r_b=0.05						

$$T_{p8} = \theta_8 \frac{aN_4 + bN_3 + cN_2 + dN_1}{N_{tot}} \tag{11}$$

Constant (a, b, c, d) derivation, correction terms due to the B/H effects and model validation is discussed in the following paragraph.

4 METHOD REFINEMENT AND VALIDATION

In order to calculate the proper constants to be inserted in Eq. (11) and to estimate the proposed model uncertainty with respect to the reference solutions, a large set of BHE configurations (240) have been considered and the related g-functions calculated with FLS spatial superposition. This approach is the same adopted in Fossa (2011, 2011b). The borefields here considered are summarized in Table 1 and they 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 10x10O).

The constant refinement procedure and validation of the method was performed by considering an overall set of M geometries, being this overall number 240. The choice of the M configurations (subdivided into rectangular and non-rectangular ones) was arbitrarily done in order to span on overall Lengths L, from few hundreds meters to about 10^4 m (N_{tot} from 3 to 100). For each configuration, different borehole spacings B/H have been employed, namely 0.03, 0.05, 0.075, 0.1 and 0.125.

The optimization was performed for a typical BHE depth equal to 100m. Additional depths up to 150m have been inserted in the process in order to take into account the influence of different Fo_H numbers (at time τ_N) on the g-function values.

The FLS g-functions have been employed to calculate the "true" temperature penalty values (symbol T_p hereafter) according to Eq. (7) and then T_{p8} formula have been adapted and improved in terms of its constants a, b, c, d. The optimum analysis was aimed at minimizing an objective function F (Eq. (12)) representative of the average of the absolute values of percentage error (T_{p8} estimates vs g-function T_p "true" values, Eq. (7)):

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

In the expression above, the subscript "k" refers to either rectangular configurations or non-rectangular ones. In order to provide a useful comparison, the different methods have been applied not only for evaluating the temperature penalty values but also the required (design) lengths. 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 (monthly average heat transfer rates extracted from ground) is depicted in Figure 1. Figure 1 shows also the yearly average together with the hourly (peak) extraction value, here estimated as 2.6 times the January value which in turn represents the monthly value Q_m to be employed in Eq. (6). The above heat load profile copes well with a 10x10 configuration; monthly value scaling has been performed to cope with different BHE configurations. The scaling factor has been adjusted through iterations until the reference overall borehole length matched the input B/H ratio. In such a way the "shape" of the heat load profile was preserved while just reducing each monthly contribution of the same percentage amount. 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 other necessary input values for all calculations are: ground conductivity and diffusivity values equal to 2.7 and 1.62E-6 respectively (SI units) and the difference ($T_{gr,\infty}$-$T_f(\tau_N)$) set to 12°C.

5 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. The refinement of values have been performed for borefield categories, say separately for: a) square and rectangular configurations (case R); b) all other configurations, say in line, plus O-shaped, plus L-configurations, plus U configurations (case non-R). The optimization attempts revealed that a correction is needed (for further reducing the errors with respect to the reference solutions) as a function of the dimensionless spacing B/H.

Furthermore the analysis of preliminary results showed that "slender" rectangular configurations (say 6x2, 8x2, 10x2 and so on) have to be ascribed to the in-line arrangements (say to non-R category) in order to obtain the best results in term of temperature penalty and borefield overall length estimation.
Optimized constants are reported in Tables (2) and (3) for rectangular and non-rectangular configurations, respectively.

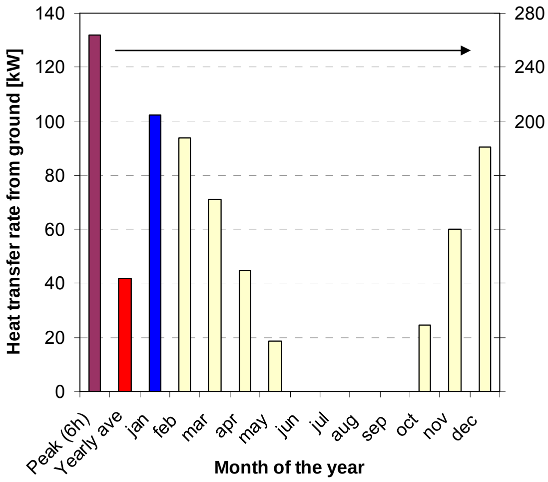


Figure 1: Reference heat load profile to the ground for BHE overall length L design.

To correctly evaluate the T_{p8} values for a variety of separating distances (say 0.03<B/H<0.125), the constants in Eq. (11) have been optimized for its specific dimensionless spacing. As can be noticed from the inspection of Tables (2) and (3), only constants a (R configurations) and c (non-R configurations) are subjected to a correction with the variation of B/H and the remaining ones have been kept invariable with the dimensionless spacing.

Table 2 Constants for R configurations as a function of the B/H ratio

R configurations					
B/H	**0.03**	**0.05**	**0.075**	**0.1**	**0.125**
a	5.41	3.90	3.07	2.42	1.93
b	0.280	0.280	0.280	0.280	0.280
c	0.450	0.450	0.450	0.450	0.450
d	0	0	0	0	0

Table 3 Constants for non-R configurations as a function of the B/H ratio

non-R configurations					
B/H	**0.03**	**0.05**	**0.075**	**0.1**	**0.125**
a	0	0	0	0	0
b	0.950	0.950	0.950	0.950	0.950
c	0.744	0.620	0.498	0.412	0.345
d	0.05	0.05	0.05	0.05	0.05

The functions that describe the variation of those constants with the dimensionless distance are reported below:

$$a \text{ (R configs)} = -2.24 \ln(B/H) - 2.73 \tag{13}$$
$$c \text{ (non-R configs)} = -0.32 \ln(B/H) - 0.0128 \tag{14}$$

The comparisons and the related validation of the present model have been made with reference to the whole set of BHE configurations, constituted by 240 different geometrical arrangements, with B/H ranging from 0.03 to 0.125. Figure 2 shows the calculated BHE overall length for the whole M set of configurations according to either the “true” T_p values (L)

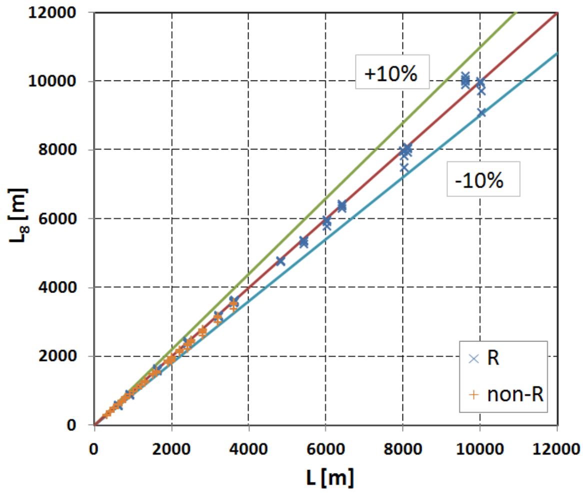


Figure 2: Calculated overall length L according to the reference T_p model and the proposed T_{p8} one. 240 BHE configurations.

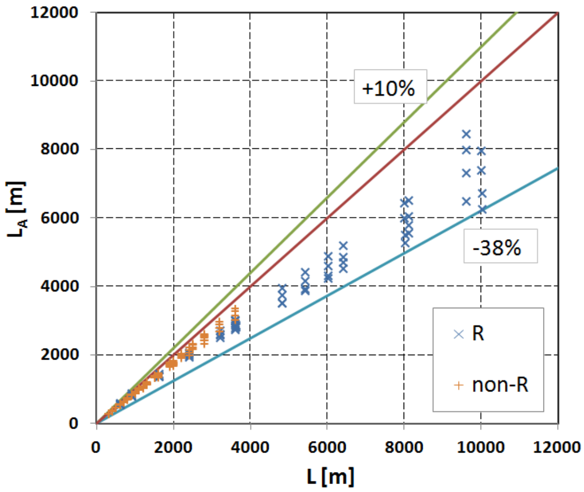


Figure 3: Calculated overall length L according to the reference T_p model and the Ashrae T_{pA} one.

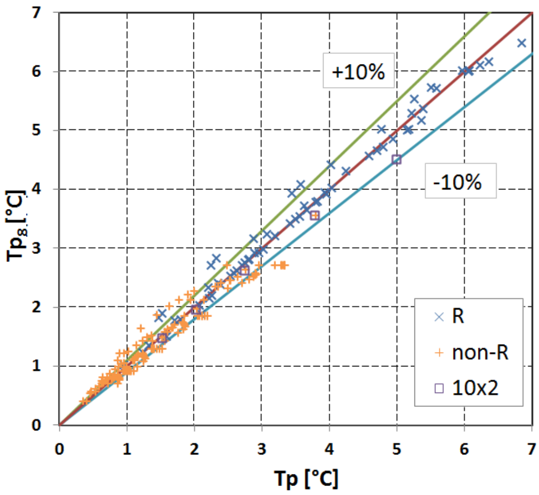


Figure 4: Calculated reference Tp values vs Tp8 ones (present model).

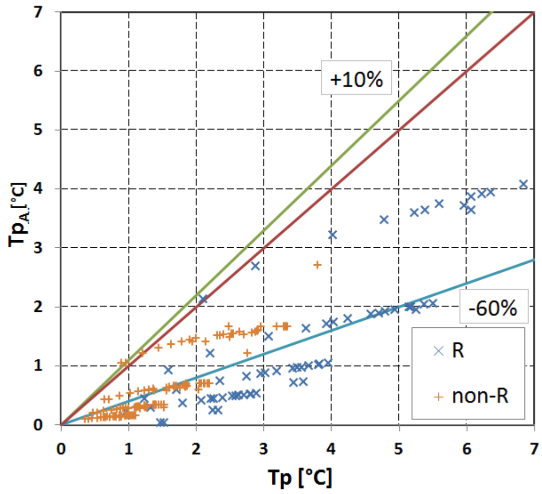


Figure 5: Calculated reference T_p values vs T_{pA} ones (Ashrae method).

or to the proposed T_{p8} ones (L_8), calculated according to the constants reported in Tables (2) and (3). In this Figure, and in the following ones, the higher lengths correspond to larger BHE fields, in terms of BHE number. Approximately 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 very 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 and L_8 is 1.34%.

Finally it can be observed that all L_8 points are well gathered within the ±10% boundaries, say they are characterised by a lower uncertainty with respect to that one which 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 12.44%, but for large matrix configurations (rectangular and square configurations, 6 BHE or more per side) the average difference is 40%. 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 6300 meters, while the “exact” estimation according to the T_p formula (7) is 10000 meters, some 37% 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 1.006. The average percentage difference is 9.26% and the standard error of estimates of T_{p8} values (with respect to T_p ones) is 0.24 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% (mean value is 54.7%, standard deviation is 40.6% and slope of the regression line is 0.63), with maximum (negative) discrepancies up to 64%.

6 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. With respect to a previous work (Fossa and Rolando, 2013) the comparison set and the calculation steps have been reviewed and extended. The overall number of BHE configurations was 240, 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 54% 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 9%. This error is even lower at high T_p values (large BHE fields) and it yields to BHE overall length estimates in very good agreement (average difference less than 1.4%) with the reference method.

Future work on this subject will include the comparison of the present method with other temperature penalty estimating procedures.

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