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An Investigation on the Effects of Different Time Resolutions in the Design and Simulation of BHE Fields

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ABSTRACT

The correct design of a field of Borehole Heat Exchangers (BHE) requires the knowledge of ground thermal properties, heat pump performance and building heating and cooling demand. The sequence of heat pulses from (to) the ground by the heat pump can be described according to different time steps, from hours to months and even years. The monthly time step approach is often the preferred design choice which involves recursive calculations (temporal superposition techniques) and the availability of precalculated temperature response factors (or g-functions) for given BHE field geometries. Such a complex computing task is usually performed thanks to commercial codes in order to fulfil a carrier fluid temperature at the end of a given time horizon, typically 10 or 25 years. In this paper the monthly design approach (EED code and TecGeo proprietary code) is compared with the three thermal pulse approach (modified ASHRAE Method Tp8) and it is demonstrated that for a representative series of case studies the three pulse calculation, easy to be performed at engineering level, is able to provide the correct BHE field overall length with 8% accuracy with respect to the reference monthly calculations.

INTRODUCTION

In ground coupled heat pump (GCHP) applications, the advantages of borehole heat exchangers (BHE) with respect to their shallow counterparts (trench and horizontal ground heat exchangers) are various, including the favourable temperatures of the soil when increasing the distance from the surface, a great freedom in choosing the best disposition of the heat exchangers in the building site, well assessed techniques for drilling the BHE, reliable models for modelling its thermal behaviour and interactions with the surrounding ground for overall system performance simulations. Concerning the theoretical part of the BHE field design process, the best approach for defining the final BHE field geometry for target system performance (in terms of given COP or overall seasonal performance factor parameters) is to employ precalculated temperature response factors (TRF) for performing ground response simulations where the heat transfer rate is variable in time.

The ground volume is very often modelled according to the thermal conduction laws. Starting from the early contributions by Carslaw and Jaeger (1947) and Ingersoll et al. (1954) that provide the ground theoretical response to simple heat sources (Infinite line and cylindrical sources, ILS and ICS, respectively), new models and related TRF have been developed in order to cope with the geometrical complexity of the real BHE fields (Eskilson 1987, Spitler and Yavuzturk 1999, Lamarche and Beauchamp 2007, Claesson and Javed 2011, Cimmino et al. 2013).

The variability of the heat loads at ground level is the consequence of the building heat demand which is

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intrinsically transient in time due to the heat pump daily and weekly duty cycles and weather effects. This variability of the heat transfer rate from (to) the ground can be tackled by applying suitable temporal superposition techniques (e.g. Spitler and Yavuzturk 1999). As it is well known the time resolution at which the heat load variation can be taken into account varies typically from hours to months, being the former approach the most reliable according to designers and researcher in this field. Since hourly simulations are time consuming from a computational point of view and also because often the input hourly data in terms (building thermal needs) are not available a common approach is to focus the analysis on a monthly time step, eventually including in the process of temporal superposition single short (hourly scale) contributions. This criterion is the one adopted in the well known calculation tools GLHEPRO (Spitler 2000) and EED (Hellstrom and Sanner, 1994). On the other hand since about 20 years a simplified model has been proposed which is based on the description of the building/ground thermal interactions in terms of only 3 contributions over 10 years (triple step model, Kavanaugh and Rafferty, 1997, Bernier 2006, Ashrae 2015). This method, known as the Ashrae method, has the fundamental advantage that it can be implemented in simple spreadsheets and does not need dedicated softwares. Recently the present Authors have developed further schemes (the T_{p8} method, Fossa and Rolando 2016, Fossa 2016) for applying the Ashrae Method to BHE field design that according to them are either more precise or faster than previous literature methods based on the evaluation of the Temperature Penalty parameter.

In this paper the Authors present a comprehensive series of comparisons related to monthly (sequence of 121 heat loads) vs triple step simulations devoted to the estimation of the required overall BHE field length. The overall time horizon is 10 years, taking into consideration different monthly profiles and a variety of BHE field geometries (e.g. square, in-line configurations). The monthly calculations are performed with either the EED code or the proprietary code TecGeo (Dalla Pietà and Fossa, 2006).

The aim of the paper is to assess the reliability of the three step approach (in terms of the T_{p8} method) with respect to the monthly approach when the BHE length is estimated based on a constraint related to the minimum temperature of the carrier fluid during the analysis period. A short discussion is finally provided about the influence of different TRFs (i.e. based on heat rate or temperature boundary conditions, see Priarone and Fossa 2016) on the final results of the design process and about the possibility to extend the T_{p8} method to longer time horizons (25 years).

THE MODIFIED ASHRAE METHOD ACCORDING TO THE TP8 MODEL

The T_{p8} method is a recent model developed by the Authors which exploits the linear properties of the conduction equation for obtaining reliable formulas able to describe the ground thermal response to BHE systems in a great variety of BHE geometries.

The model, its accuracy and the comparison with literature similar methods are described in details in three papers by the Authors (Fossa and Rolando 2015, Fossa and Rolando 2016, Fossa 2016). Here in the following the main calculation steps of the T_{p8} approach are briefly presented.

Table 1. Ashrae Modified Tp8 model: formula set

Quantity	Expression					
Required length L of the BHE field (10 years)	$L = \frac{\{\dot{Q}_y R_y + \dot{Q}_m R_m + \dot{Q}_h (R_h + R_{bhe})\}}{T_{gr,\infty} - T_{f,ave}(\tau_N) - T_p} \quad (1)$ <p>(as in the original Ashrae Method 2015 and Bernier 2006)</p>					
Ground thermal resistances R_y, R_m, R_h	Evaluated according to the G solution (ICS model) values at given time intervals, as in the original Ashrae Method					
Temperature Penalty T_p	T_p is expressed through an auxiliary temperature variable θ_8 and as a function of the BHE field geometry (N_1, N_2, N_3, N_4 parameters) $T_p = \theta_8 \frac{aN_4 + bN_3 + cN_2 + dN_1}{N_{tot}} \quad (2)$					
Auxiliary temperature variable	$\theta_8 = \dot{Q}_y \frac{E_1(\tau_N, B) + E_1(\tau_N, B\sqrt{2})}{\pi k_{gr} L} \quad (3)$					
Constants a, b, c, d (Fossa and Rolando, 2016)	Rectangular 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
	Non-Rectangular configurations and slender Rectangular (6x2, 7x2, 8x2 and so on)					
	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	
Evaluation of the G function (Fossa 2016)	$G = \sum_{j=0}^6 c_j \text{Log}_{10}(Fo_{rb}) \quad (4)$ <p> $c_0 = 1.2777\text{E-}01$ $c_1 = 1.0812\text{E-}01$ $c_2 = 3.0207\text{E-}02$ $c_3 = -2.3037\text{E-}03$ $c_4 = -1.4459\text{E-}03$ $c_5 = 3.6415\text{E-}04$ $c_6 = -2.4889\text{E-}05$ </p>					
Evaluation of the Fourier number Fo^* for calculating the E_1 function, Eq. (2)	$Fo^* = \frac{\alpha_{gr} \tau_N}{R^2} \cdot \left(\frac{H_{ref}}{H} \right) \quad (5)$					

As it well known the Ashrae method allows the calculation of the BHE field overall required length L in terms of the ground properties (being k_{gr} , α_{gr} and $T_{gr,\infty}$ its thermal conductivity, diffusivity, and undisturbed temperature, respectively), the building heat transfer rates \dot{Q} to (from) the ground in three time steps (10 years, 1 month, 6 hours, subscripts y, m, h respectively), the borehole effective thermal resistance R_{bhe} and the target carried fluid temperature $T_{f,ave}$ at the end of the analysis period (τ_N equal to 10 years plus 1 month plus 6 hours). The Ashrae method is based on the calculation of the ground thermal resistances R_y , R_m and R_h starting from the G solution (also known as the ICS solution, Ingersoll et al. 1954) and introduces a correction term (the Temperature Penalty T_p) that represents the

necessary correction to the simple G solution when it is employed for describing complex borefield geometries in the late period τ_N (Fossa 2016).

The complete set of formulas for calculating the required length is given in Table 1.

Further symbol meanings are provided: E_1 is the exponential integral (Abramovitz and Stegun, 1964), B is the BHE interdistance, r_b is the BHE radius, H is the actual BHE depth and H_{ref} is a reference depth set equal to 100 m, N_4 , N_3 , N_2 and N_1 are the number of boreholes (in the BHE field) surrounded by only 4 other ones, only 3 other ones, and so on, respectively.

THE PROCEDURE FOR COMPARING THE DESIGN RESULTS IN TERMS OF DIFFERENT TIME RESOLUTIONS

Temporal superposition is a well known technique for exploiting base solutions of the transient conduction problem for solving GCHP design tasks when the ground/BHE system is subjected to non constant heat load profiles. Even if hourly load simulations are considered the best way to simulate the borefield response and study the GCHP plant performance very often such an analysis is performed based on the knowledge of the building heating and cooling monthly loads. Such thermal loads are usually easily accessible through steady state and even transient simulations of the building (and its thermal plant) interactions with the external environment. When the monthly load approach is applied to the BHE field design problem an additional peak load is usually included in the superposition scheme as discussed in recent studies by the Oklahoma State University research group (e.g. Cullin and Spittler, 2015).

The resulting algorithm is the one embedded in commercial codes like EED or GHLEPRO and in the proprietary code TecGeo developed at the University of Genova Italy:

$$T_{f,ave}(\tau_N) = T_{gr,\infty} + \dot{Q}'_{peak} R_{bhe} + \frac{1}{2\pi k_{gr}} \sum_{i=1}^N (\dot{Q}'_i - \dot{Q}'_{i-1}) g(Fo(\tau_N - \tau_i)) + \frac{1}{2\pi k_{gr}} (\dot{Q}'_{peak} - \dot{Q}'_N) g_{peak}(Fo(\tau_{peak})) \quad (6)$$

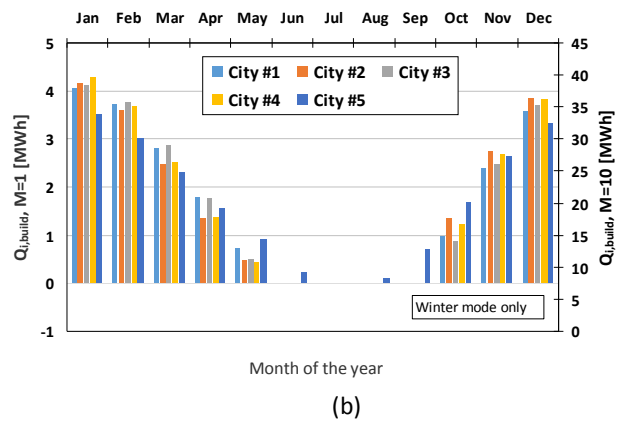
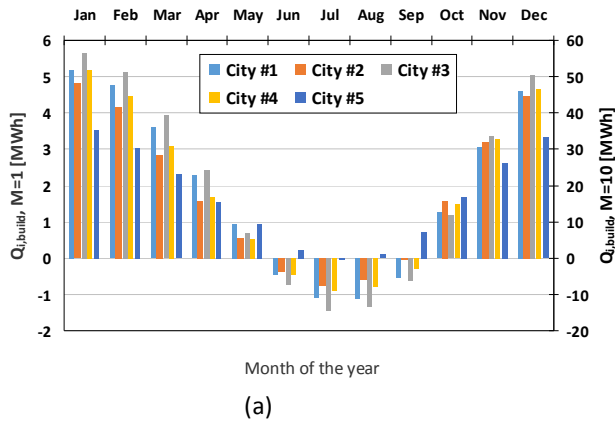
where the \dot{Q}'_i are the monthly average heat rates (per unit length) to the ground and g is the g-function of that BHE field, i.e. the TRF pertaining that borefield assembly in terms of depth H , spacing B , radius r_b and disposition (e.g. rectangular, in line, and so on). In the above expression \dot{Q}'_{peak} is the peak load in the worst operating conditions, τ_{peak} its duration and g_{peak} the TRF employed for describing the ground response to this short thermal pulse.

The related heat rates \dot{Q}'_y and \dot{Q}'_m of the Ashrae method can be calculated from the 12 monthly values \dot{Q}'_i as the average along the year and as the worst month condition, respectively. The peak load \dot{Q}'_h is just the corresponding quantity \dot{Q}'_{peak} multiplied by the BHE depth H .

In this paper two design approaches are compared related to a time horizon of 10 years.

In the reference procedure 121 monthly heat loads are taken into account and they represent 12 monthly loads (from January to December) that replicates for 10 years. The 121st term is representative of the January contribution of the 11th year, in order to cope with the τ_N horizon of the Ashrae approach.

The second approach is the T_{p8} Ashrae method (Table 1 equation set) which takes into account the average term \dot{Q}'_y and the (worst) month contribution \dot{Q}'_m which corresponds in the present analysis to the January monthly heat load.. Both procedures include the same peak load. Since the Ashrae method cannot account for multiple peak loads, in monthly simulations a single peak load is superposed at the above worst monthly contribution. On the other hand, while searching for the minimum fluid temperature during the years, the selection of a single peak load applied



Figures 1 Monthly load profiles taken as input values for BHE field design.
Condition (b) refers to heating operations only

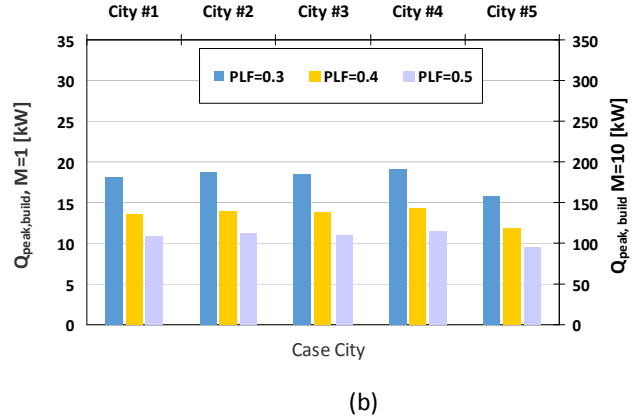
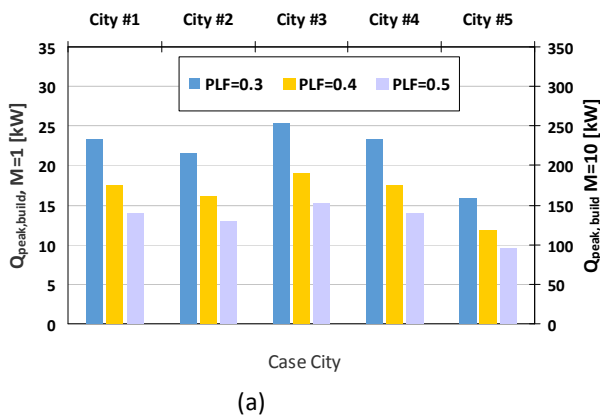


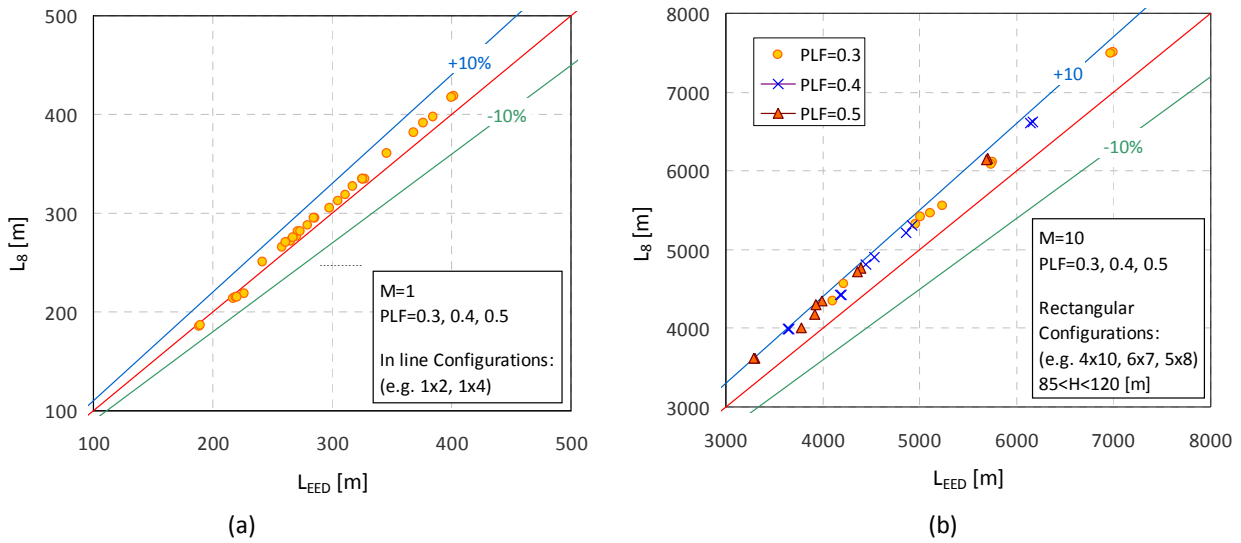
Figure 2 Peak loads taken as input values for BHE field design.
Three different conditions have been considered as the effect of different partial load factors (PLF)
Condition (b) refers to heating operations only

to the “worst” month is typically enough and to take into consideration additional peak loads it is not necessary.

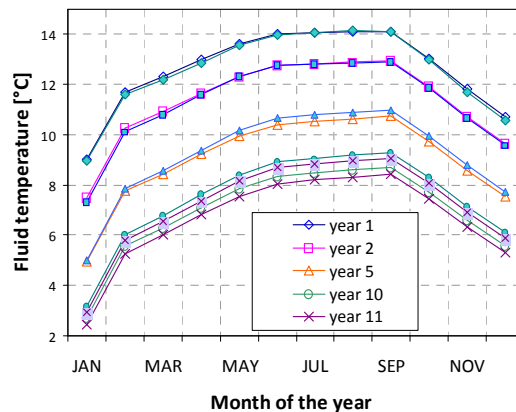
A series of test cases have been taken into account in terms of monthly heat load and peak load distributions to cope with the typical heat demand profiles of Italian sites. Heat monthly profiles has been calculated based on local weather conditions while the peak load has been set equal to the January average heat rate divided by a partial load factor (PLF) parameter which has been arbitrary chosen in a range of typical values.

Figure 1a and 1b show the monthly load distributions (energy per month required by the building) for the 5 case cities taken into consideration and they refer to 2 different building sizes, characterized by a heat demand multiplier M equal to 1 and 10, respectively. Figure 1a is a general case where either the heating and cooling loads are taken into consideration while Figure 1b refer to a condition where the GCHP duty is only heating, say to work only in winter mode. This last condition is addressed to emphasize the role of the correct evaluation of the T_p term (Fossa 2016), which is proportional to \dot{Q}_y and hence gains importance when the building yearly load profile is markedly unbalanced (winter only or summer only operating modes).

Figures 2a and 2b show the distribution of the peak loads (heat rate required by the building, heating operation only is case b) for the 5 case cities and considering a PLF parameter assuming the values 0.3, 0.4 and 0.5.



Figures 3 Calculated overall BHE length L with the reference method (EED) and the Ashrae/ T_{p8} one. $M=1$ (a) and $M=10$ (b)



Figures 4 Monthly fluid temperature along the years as calculated with different monthly algorithms. City #2, $PLF=0.4$, $M=10$, winter only loads. Filled symbols: EED predictions; open symbols: TecGeo predictions

In spite of the fact that the selected input data set for the present design calculations is necessarily arbitrary it can be stated that it is a reasonably comprehensive of many working conditions encountered by GCHP plants in Europe. Further data input are the seasonal performance factor (SPF) which has been set to 4, R_{bhe} set to 0.10 mK/W , k_{gr} set to 2.5 mK/W , α_{gr} set to $11e-7 \text{ m}^2/\text{s}$ and the undisturbed local ground temperature of each case city ($T_{gr,\infty}$ range: 10 to 16°C).

The calculations have been performed for attaining a minimum carrier fluid temperature of 3°C when the BHE field is characterized by interdistances B equal to 5 meters. The BHE field geometry has been selected among the rectangular and in-line configurations (e.g 2x1, 3x2, 4x10, 6x7) in order to fulfill the carrier fluid constraint with BHE depths not exceeding the range 85 to 120 m.

RESULTS

Simulations of the fluid temperature evolution in time have been performed with the EED code while imposing the minimum allowed fluid temperature (3°C) for the given BHE field configuration. The same constraint have been applied to the T_{p8} algorithm where the constants a , b , c , d and the BHE types N_1 , N_2 , N_3 , N_4 have been calculated as a function of the BHE field configuration, the same of the corresponding EED case. With both procedures the overall BHE lengths (and hence the corresponding BHE depths) have been evaluated.

The peak load duration has been set equal to 6 hours, as suggested in the original Ashrae method.

Figure 3a shows the final overall BHE length as calculated with both the EED code and the modified Ashrae method for the 5 case cities, at different PLF numbers (e.g. at different peak loads for given base load set) when the base load multiplier M is equal to 1 (monthly load input values: left y-axis of figures 1a and 1b). The resulting BHE configurations resulted 2x1, 3x1 and 4x1 for overall lengths not exceeding 500 m. It can be noticed that the monthly design procedure and the three pulse one give practically the same results, with minor discrepancies in the 3% range. This error is related to the intrinsic error in T_{p8} method for small BHE fields as a consequence of its best fit constants.

Figure 3b is the $M=10$ version of the previous one: the building heat loads are greater and the resulting BHE fields are larger (up to 7x10 BHEs). Here the agreement among the reference EED calculation and the Ashrae/ T_{p8} one is still good but major differences arise, of the order of 8% (in the direction of oversizing the BHE system).

The above discrepancies could be ascribed to the different TRFs employed in EED with respect to those employed during the optimum search of T_{p8} constants (Table 1). As deeply discussed in Fossa and Rolando 2015 and Fossa and Priarone 2016, TRFs (g-functions) can be calculated according to different boundary conditions (i.e. at imposed heat rate, as in TecGeo and T_{p8} , or temperature, as in EED) but in the Fo range pertaining to 10 year horizons they should not differ meaningfully.

Figure 4 finally shows the comparison between the time evolution of the carrier fluid temperature for the city #2, $M=10$, $PLF=0.4$ as calculated by EED and by the proprietary code TecGeo. The two codes should implement the same overall algorithm while employing different g-function databases. In particular TecGeo works with the same g-functions employed for best fit optimization of T_{p8} method constants. The BHE configuration in this case is 6x7, B is equal to 5 m and $H=107$ m. As can be observed the temperature profiles are in close agreement and the maximum fluid temperature difference is about 0.6°C at January of the 11th year. The exact agreement in terms of minimum fluid temperature it would be obtained by setting $H_{EED}=103$ m. On the other hand when TecGeo is employed for the same case for calculating the required length, the comparison with the T_{p8} prediction reveals a difference of less 3% ($L_{TG}=107$ m, $L_8=110$ m). It is interesting to notice that for the same input data the original Ashrae method (Kavanaugh and Rafferty, 1997) would provide an overall BHE length of only 82 m..

These evidences deserve further investigation and maybe a critical review of EED database of TRF functions.

Finally it is worth stressing that a series of simulations have been carried at different τ_{peak} values (from 3 to 12 hours) that provided results still in agreement among them (again 8% differences between EED and T_{p8} predictions), thus demonstrating once again the reliability of the modified Ashrae method.

CONCLUSIONS

A series of case tests related to the design of BHE fields have been considered in order to compare the results obtained with a monthly heat load approach with those provided by a modified version of the Ashrae method (the T_{p8} method). The simulations have been performed with respect to a 10 year scenario (121 months) and considering various BHE field configurations, from small in-line geometries (1x2 to 1x4) to large rectangular dispositions (up to 7x10). The overall BHE length ranged from few hundreds meters to 7 thousands.

The paper demonstrates that the modified Ashrae method is able to provide similar results (differences within 8%) with respect to the reference calculation procedure (EED code) when the design target is the overall BHE length for given minimum allowed fluid temperature.

The differences in the predicted lengths can be partially ascribed to the different sets of g-functions employed by the reference code and the present procedure: further investigations will be devoted to clarify these aspects.

Current work on the T_{p8} method is finally addressed in the direction of extending its applicability to a 25 year horizon through model tuning in terms of constants and superposition scheme.

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NOMENCLATURE

B	=	BHE separating distance (m)	
F_0	=	Fourier number, $F_0 = (\alpha\tau)/r_b^2$	(-)
F_0^*	=	Modified Fourier number, $F_0^* = [(\alpha\tau)/R^2](H_{ref}/H)$, Eq. 3 and 5	(-)
E_i	=	exponential integral	(-)
G	=	ICS temperature response factor	(-)
H	=	BHE depth	(m)
k	=	Thermal conductivity	(W/mK)
L	=	BHE overall length	(m)
M	=	heat demand multiplier	(-)
N	=	BHE number	(-)
PLF	=	partial load factor	(-)
Q	=	Heat	(J or MWh)
\dot{Q}	=	Heat transfer rate	(W)
\dot{Q}'	=	Heat transfer rate per unit length	(W/m)
r_b	=	Borehole radius	(m)
R	=	Distance parameter in T_{p8} scheme (Eq. 3). R is equal to B or $B\sqrt{2}$	(m)
R_j	=	Thermal resistance	(mK/W)
T	=	Temperature	(°C or K)
T_p	=	Temperature penalty parameter	(°C or K)
α	=	Thermal diffusivity	(m ² /s)
θ_s	=	Auxiliary temperature variable	(°C)
τ	=	Time	(s)

Subscripts

∞	=	undisturbed conditions
δ	=	T_{p8} method
<i>build</i>	=	at building side
<i>bbe</i>	=	relative to the BHE
<i>EED</i>	=	EED code
<i>fluid, ave</i>	=	of the carrier fluid, average in and out value

<i>gr</i>	=	ground
<i>h</i>	=	hourly term (6 hours)
<i>m</i>	=	monthly term (1 month)
<i>peak</i>	=	peak term
<i>ref</i>	=	reference length (100 m)
<i>TG</i>	=	TecGeo code
<i>y</i>	=	yearly term (10 years)

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