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Extending the ASHRAE method to a 25 year horizon through the Tp8 model for temperature penalty accurate estimation

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ABSTRACT

The accurate design of Borehole Heat Exchangers (BHE) fields in ground-coupled heat pump (GCHP) systems is crucial for ensuring long-term performance. Traditional sizing methods, such as the ASHRAE method as modified by ASHRAE-T_{p8} version, consider the annual building heating and cooling demand over a 10-year time horizon by applying the temporal superposition of 3 aggregated thermal pulses of different durations. The present paper aims to clarify how the ASHRAE-T_{p8} method could be adapted to be employed over a 25-year plant operation horizon. Temperature penalty estimations are compared with "real" precalculated temperature response factors (g-functions) through the minimization of a suitable objective function. Optimized constants for the present new ASHRAE-T_{p8} method are derived, enabling its easy adaptation for the 25-year time period. Comparisons with EED and GLHEPRO commercial software results demonstrate the reliability of this improved method, with borefield length estimations accurate within 7% and 6% respectively. The results reported in the present paper lead to easily inferring the error in terms of overall length and borehole depth that would be obtained by employing the design process proper of the 10-year reference period when the 25-year time horizon is considered. The methodology is in general demonstrated to be applicable to different time frames.

INTRODUCTION

The long-term performance of a ground-coupled heat pump (GCHP) system relies on the accurate sizing of the borehole heat exchangers (BHEs) field. Common commercial calculation software (Spitler 2000, Hellstrom and Sanner 1994) typically utilizes dimensionless pre-calculated solutions known as Temperature Response Factors (TRF) or g-functions (Eskilson 1987) to describe fluid and ground thermal responses to the borehole field.

Research groups, led by Professors Spitler and Bernier (Yavuzturk and Spitler 1999, Bernier 2006, Cimmino and Bernier 2014), pioneered the use of thermal load aggregation techniques and temporal superposition methods. The widely adopted ASHRAE method (ASHRAE Handbook 2015), proposed by Kavanaugh and Rafferty (1997), forms the basis for sizing BHE fields. Unfortunately, comparisons between Eskilson's g-functions and the ASHRAE method by Cullin et al. (2015) revealed errors from -21% to 167%. Staiti (2014) found ASHRAE overestimating BHE size by up to 27% compared to GLHEPRO (Spitler 2000). Design method selection and uncertainties in input parameters (e.g., ground thermal conductivity, fluid temperature levels, borehole thermal resistance) can impact sizing by 14% to 27% (Staiti

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2014).

Fossa and Rolando (2015) and Fossa (2017) proposed a method for computing temperature penalty with an average deviation of less than 10% around the true values line (i.e. extrapolated by TRF) while keeping the simplicity proper of the original ASHRAE method. Furthermore, Fossa and Rolando (2015) found that the original ASHRAE method can yield important errors in the BHE overall length evaluation with an average difference with reference to the right value up to 40%. The modified ASHRAE-T_{p8} method, as embedded into the free web app (GeoSensingDesign.org), demonstrated to provide the correct BHE field overall length within 5% with respect to the reference monthly step thermal loads calculations performed with EED and GLHEPRO for a wide range of monthly profiles and different BHE field configurations (Fossa et al. 2023).

As confirmed by the most recent literature (Zhi et al. 2022, Zhang et al. 2019), the design methods based on the temporal superposition of 3 aggregated thermal pulses and the temperature penalty T_p, suitably introduced to take into account the thermal effects of multi-borehole configurations, are usually restricted to a 10-year life cycle for evaluating the correct sizing of the BHE field such to guarantee the desired performance of the GCHP at its tenth year of operation. On the other hand, relevant literature investigations by (Eskilson 1987, Kavanaugh and Rafferty 1997, Rybach and Sanner 1999, Rybach and Eugster 2002) declare that the BHEs field should be sized for achieving the correct operation for at least 30 years. In this regard, Kurevija et al. (2012) in their comparison between Eskilson's g-functions and the original ASHRAE method for one building in Croatia demonstrated that the ASHRAE method underestimates the sizes when a 30-year design is carried out.

The updated ASHRAE-T_{p8} method herein introduced extends the time horizon to 25 years, addressing the need for BHE field sizing beyond the standard 10-year life cycle. The method allows setting the desired Coefficient of Performance (COP) value for the 25-year ASHRAE horizon, striking a balance between engineering requirements and the goal of achieving correct operation for at least 30 years. Example calculations, employing the updated ASHRAE-T_{p8} method with a 25-year time horizon, are presented. An easy comparison in terms of overall length and BHE depth between the design process that considers the 25-year time horizon and the one related to the standard 10-year time horizon can be inferred. The study, conducted on typical European building structures (according to the Tabula webtool database, TABULA WebTool) with hourly heat load profiles from EnergyPlus (energyplus.net) simulations, includes both Rectangular (R) and non-rectangular (Non-R) borehole configurations. The robustness and feasibility of the updated method, applicable for future design guidelines, is demonstrated by comparing the results with those provided by EED and GLHEPRO commercial codes. It is expected that it may be considered a new standard by the ASHRAE Society (ASHRAE Handbook 2015) and adopted by the Italian standard UNI 11466 (Italian guidelines 2012) to ensure properly sized GCHP plants for correct operation for at least 25 years.

THEORETICAL BACKGROUND

The standard triple-step sizing models consider the entire annual monthly step load profile shrunk into 3 contributions over 10 years. These aggregated methods consider 3 representative thermal loads of the building obtained from hourly, daily or monthly load profile information in heating and cooling and employ the Infinite Cylindrical Souce (ICS, Ingersoll et al. 1954) solution (i.e. TRF) to tackle the Fourier problem, suitably corrected by the introduction of the "temperature penalty" T_p for a reliable description of the thermal response of complex geometry BHE fields considering a 10-year life cycle, as described in detail in Fossa (2017). Among the classical analytical solutions of the heat conduction equation related to an infinite source injecting a constant and uniform heat transfer rate per unit length $\dot{Q}'$ into an infinite medium, the ones related to the Infinite Line Source (ILS, Carslaw and Jaeger 1959, Ingersoll et al. 1954) and ICS models for borehole heat transfer are the most used. The corrective T_p variable is needed and introduced to suitably account for the thermal interactions between adjacent boreholes related to 2D and 3D effects in the ground temperature field. The overall considered time horizon covered by the 3 thermal pulses and the related heat load proper of these

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aggregated methods in their standard form is 10 years of yearly load ($\dot{Q}_y$), 1 month of the most demanding monthly heat load ($\dot{Q}_m$), and a heat pulse 6 hours long corresponding to the most demanding daily heat load ($\dot{Q}_h$) related to the most demanding month. According to the original ASHRAE method, Eq. (1) allows the evaluation of the overall borehole field length L (Bernier 2006):

$$L = \frac{\{\dot{Q}_y R_y + \dot{Q}_m R_m + \dot{Q}_h (R_h + R_b)\}}{T_{gr,\infty} - T_{f,ave}(\tau_n) - T_p} \quad (1)$$

Where R_b is the borehole thermal resistance, R_y R_m R_h are the thermal resistances [mK/W] corresponding to the dimensionless Fourier, Fo_τ, time intervals proper of the original method ($Fo(r_b)$ evaluated at τ_n= 10 years + 1 month + 6 hours, τ_{m+h}=1 month + 6 hours, τ_h=6 hours) and evaluated according to the ICS model. The temperature penalty T_p can be expressed as a function of 4 main parameters (Fossa 2011) as:

$$T_p(L) = \frac{\dot{Q}_y \Delta\Gamma}{L k_{gr}} \quad (2)$$

Where in particular:
$\Delta\Gamma = \frac{g(\tau_n)}{2\pi} - G(\tau_n)$ is the error due to the use of the G temperature transfer function proper of the ICS solution correspondingly to the time τ_n with respect to a "true" Eskilson-type borefield g-function (Eskilson 1987) able to describe the thermal response of multiple, finite length, ground heat exchangers.

Worth noticing, one could use directly the g-functions with no need to rely on G and its correction T_p (Ahmadfard and Bernier, 2014), provided that the full set of g-functions is available and the final geometry of the BHE field is already known.

The above concepts have been discussed recently in the interesting book by Lamarche (2023).

The complete list of equations proper of the modified ASHRAE-T_{p8} method is presented in detail in papers by the present Research group (Fossa 2017, Fossa and Rolando 2015, Fossa et al. 2023) to which the Reader is addressed. These equations, as well as the entire calculation structure, are also effectively employed in its updated version for marking a 25-year time horizon, provided that the new constants from the optimal search process are employed (see the next Section of the present paper for details). It is important to highlight that Fossa and Rolando (2015) proposed a model based on the ILS solution (and its exponential integral function E_1) for obtaining a first estimation of the auxiliary parameter they named θ_8 useful for computing the temperature penalty T_p. The θ_8 parameter is evaluated considering a basic geometry characterized by a central borehole surrounded by up to 8 neighbor ones in a regular matrix arrangement and by applying the spatial superposition of temperature solutions related to 8 BHEs around the central one as explained by Fossa (2017), where B is the distance among boreholes.

$$\theta_8 = \frac{\dot{Q}_y [E_1(Fo(\tau_n, B)) + E_1(Fo(\tau_n, B\sqrt{2}))]}{\pi k_{gr} \cdot L} \quad (3)$$

The θ_8 parameter is then refined with an additional formula that necessarily takes into account the real BHE field arrangement through constants obtained from g-function analysis. Thus, the temperature penalty T_{p8} of a generic BHE field configuration can be expressed as:

$$T_{p8} = \frac{\theta_8 (a N_4 + b N_3 + c N_2 + d N_1)}{N_{tot}} \quad (4)$$

Where:
N_j is the number of boreholes surrounded by j other boreholes and automatically assigned (for details see Fossa 2017 and Fossa et al. 2023)
a, b, c and d are T_{p8} coefficients (see Fossa and Rolando 2015)

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N_{tot} is the total number of boreholes.
Since the total length of BHE field L is present in Eq. (3) for the θ_8 computation, it is clear that the modified ASHRAE-T_{p8} method is an iterative procedure whose convergence value leads to the overall BHE field length L provided by Eq. (1). The whole method marking a 10-year time horizon is embedded and available as a web application (BHEDesigner8), completely for free, at www.geosensingdesign.org (GeoSensingDesign.org).

THE UPDATED VERSION OF THE MODIFIED ASHRAE-T_{P8} METHOD

All the methods that involve modifications to the standard ASHRAE method, like the one proposed by Ahmadfard and Bernier (2014,2018) and the one by Fossa and Rolando (2015,2017) consider a plant life span equal to 10 years. The method herein proposed represents the natural development of the modified ASHRAE-T_{p8} method by Fossa (2017) and Fossa and Rolando (2015), the first that considers a time horizon of 25 years for sizing the BHE field. The overall considered time horizon covered by the 3 thermal pulses and the related heat load decomposition proper of the $T_{p8,25y}$ method (as shown in Figure 1) is 25 years of yearly load ($\dot{Q}_y$), 1 month of the most demanding monthly heat load ($\dot{Q}_m$), and a heat pulse 6 hours long corresponding to the most demanding daily heat load ($\dot{Q}_h$) related to the most demanding month.

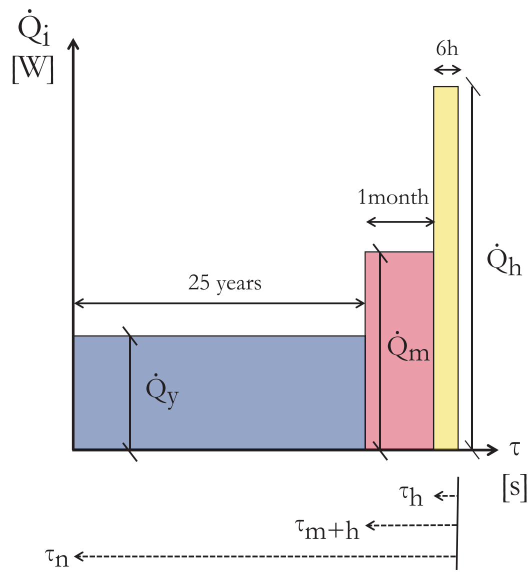

Figure 1 The 3 heat transfer rates considered by the $T_{p8,25y}$ method $\dot{Q}_y$, $\dot{Q}_m$, $\dot{Q}_h$. The x-axis is not to scale.

The same Equations (1) to (4) proper of the method still apply while the new time reference τ_n related to the new time horizon is considered (τ_n=25 years+ 1 month + 6 hours). The computation of the R_y thermal resistance is updated with the Fo_τ, corresponding to the new reference τ_n. The new constants *a*, *b*, *c*, *d* to be adopted in Eq. (4) have been determined via an optimal search process aimed at minimizing the overall gap between the temperature penalty $T_{p8,25y}$ and the correct $T_{p,g}$ "true" value: the former has been calculated according to Eq. (4) by assigning initial default values to the constants *a*, *b*, *c*, *d,* while the latter results from the 25-year Eskilson "exact" g-functions (Eskilson 1987). The approach has been applied to a wide range of different borehole heat exchanger (BHE) field configurations (R and Non-R). The gap minimization between temperature penalty parameters can be carried out since the *F(a,b,c,d)* objective function expressing the average of the absolute values of percentage error of the $T_{p8,25y}$ by Eq. (4) with respect to the reference g-function $T_{p,g}$ "true" values (Fossa and Rolando 2015) by Eq. (2) has been identified:

$$F(a,b,c,d) = \frac{1}{M_k}\sum_{j=1}^{M_k}\frac{|T_{p,g,j}-T_{p8,25y,j}|}{T_{p,g,j}} \qquad (5)$$

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It is possible to obtain via optimal search analysis the constants *a, b, c, d* (4 optimized constants for the whole "M_k" rectangular configurations and other 4 optimized constants for the whole "M_k" non-rectangular ones) that minimize the *F(a,b,c,d)* objective function as the dimensionless BHE spacing B/H change in the range 0.03<B/H<0.125 (B is the center to center spacing between boreholes and H is the borehole depth). The R and non-R configurations considered by the $T_{p8,25y}$ method herein proposed are those reported in (Fossa et al. 2023, GeoSensingDesign.org). In the optimal search analysis, a reference BHE depth (H_{ref}) of 100 m has been considered in the g-function evaluation. As proposed by Fossa and Rolando (2015), for BHEs with different depths the $T_{p8,25y}$ method considers the corrected Fourier number Fo^* to be used in the calculation of the E_1 function for Eq. (3):

$$Fo^* = Fo(\tau_n, R) \cdot (\frac{H_{ref}}{H}) \quad (6)$$

Where R can be B or B√2 in a regular matrix arrangement constituted by 8 BHEs around the central one.

The optimal search analysis has been applied separately to 135 rectangular (R) and 165 non-rectangular (non-R) configurations considering 5 different dimensionless distances B/H. Table 1 and Table 2 show the obtained constants for R and non-R configurations respectively. It is possible to interpolate the results for any B/H between 0.03 and 0.125 for R and non-R configurations.

Rectangular configurations					
B/H	0.03	0.05	0.075	0.1	0.125
a	5.741	3.656	2.395	1.757	1.333
b	0.172	0.193	0.328	0.050	0.050
c	0.121	0.199	0.050	0.334	0.291
d	0	0	0	0	0

Table 1 Constants to be employed in Eq. (4) for Rectangular (R) configurations.

Non-Rectangular and slender Rectangular configurations					
B/H	0.03	0.05	0.075	0.1	0.125
a	0	0	0	0	0
b	1.063	0.774	0.575	0.438	0.356
c	0.737	0.510	0.370	0.263	0.198
d	0.011	0	0	0	0.015

Table 2 Constants to be employed in Eq. (4) for non-R configurations.

In the next extended version of the present paper, the Authors are working to improve the method by calculating additional constants for the subgroups pertaining to the non-rectangular family of BHE arrangements.

VALIDATION OF THE $T_{P8,25y}$ METHOD AND DISCUSSION OF RESULTS

Dedicated examples of BHE field design calculations considering typical European building structures (by Tabula webtool database) and hourly heat load profiles (by EnergyPlus simulations) are reported in the present section and compared to the one provided by EED and GLHEPRO commercial codes to demonstrate the robustness of the $T_{p8,25y}$

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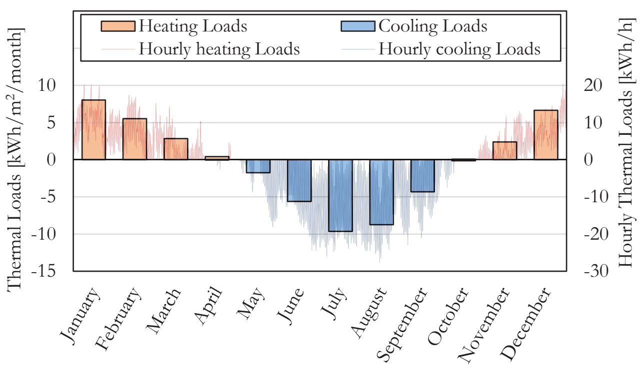
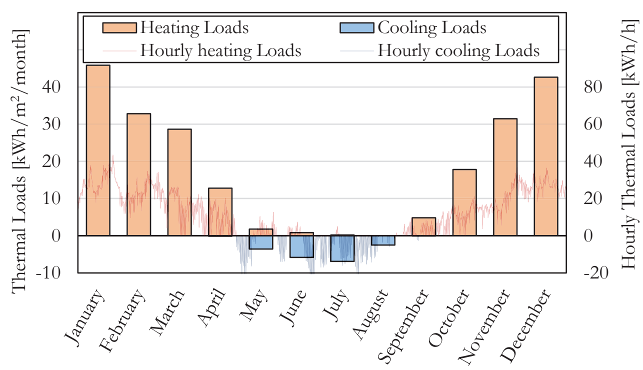
method for extended time horizons (i.e. 25 years). Furthermore, the same example calculations, are employed for comparing the results obtained on the standard 10-year time horizon and those obtained on the 25-year time horizon in terms of overall BHE length and single BHE depth. Two typical European building structures are considered for the present calculations among those reported in Fossa et al. (2023), according to Tabula webtool database; the hourly heat load profiles are obtained from EnergyPlus simulations, and the design process involves both Rectangular (R) and non-rectangular (Non-R) borehole configurations. In particular, the examples reported are related to a typical Italian multi-family house built in a historical period between 2006 and the present (Figure 2a), and a Swedish multi-family house built in a historical period included between 1996-2005 (Figure 2b). Worth noticing, the Italian case is characterized by a more balanced heat load profile (i.e. heating vs cooling) along the year.

A third example characterized by a BHE field serving 14 units of Italian multi-family houses is herein reported. This is to force the algorithm to design an extended BHE field for which the $T_{p8,25y}$ evaluation with the proposed method by Eq. (4) incorporating the optimized constants could be more critical in comparison to the correct $T_{p,g}$ "true" value calculated by Eq. (2) exploiting the"exact" g-functions.

The internal temperature of buildings is set to be maintained in the range 20-26°C all year long, for both the heating and the cooling season. The monthly heat loads resulting from EnergyPlus simulations as outputs and the peak heat loads in heating and cooling estimated according to the approach proposed by Cullin and Spitler (2011) are those reported in Fossa et al. (2023) according to Appendix 1. For the third case characterized by 14 units of Italian multi-family houses, the heat loads are multiplied by 14. The input data, building loads included, are the same for the 3 sizing methods considered (i.e. $T_{p8,25y}$, EED and GLHEPRO) and are reported in detail in Fossa et al. (2023).



(a)



(b)

Figure 2 Hourly building thermal loads profiles and monthly total thermal load per unit usable floor area for an Italian (a) and Swedish (b) multi-family house. Predictions from EnergyPlus simulations.

To compare the results and cover the same time horizon proper of the ASHRAE-$T_{p8,25y}$ method, EED and GLHEPRO simulations are run over 301 months (25 years and 1 month) and 6 additional hours of peak load so that the required borehole length is found for a given minimum (or maximum) average fluid temperature $T_{f,ave}(\tau_n)$ which appears in Eq. (1). In such a way, the monthly step software (EED and GLHEPRO) stops their search for the required length at the 301st month. The results in terms of estimated BHE depths H and overall BHE field lengths L related to the BHE configurations (R and non-R) characterizing the three specific cases are reported in Figures 3(a) and 3(b) respectively. The estimated values by the three methods reported in Figure 3 refer to a time horizon of 10 and 25 years and to heat loads pertaining to buildings and climates of Sweden and Italy.

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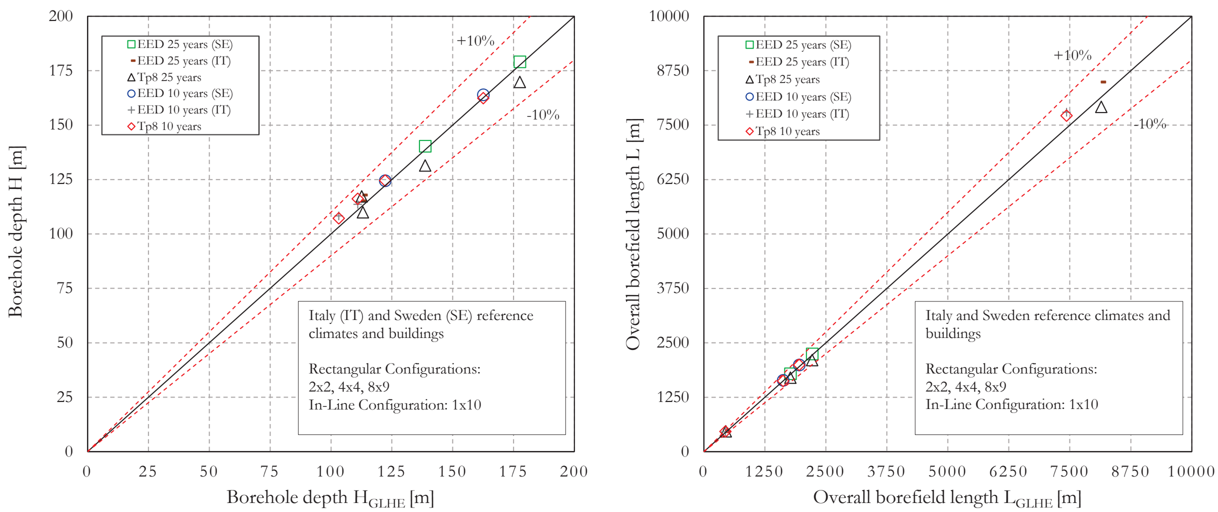

(a) **(b)**

Figure 3 BHE depth H estimations from the present T_{p8} method vs EED and GLHEPRO predictions (a). Overall BHE field length L estimations from the present T_{p8} method vs EED and GLHEPRO predictions (b). R and non-R configurations.

The results by the $T_{p8,25y}$ method in terms of BHE depth H and overall borehole field length L can be easily compared to the ones by EED and GLHEPRO as reported in Figures 3(a) and 3(b). From Figures 3 is easy to infer the error that would be obtained by employing the design process proper of the standard 10-year time horizon when a 25-year time horizon is considered for each specific case. In general, the agreement between EED and GLHEPRO is guaranteed since they exploit the same g-functions. The percentage increase in terms of estimated BHE depth H and overall BHE length L by $T_{p8,25y}$ tends to be lower than the one computed by EED and GLHEPRO. The percentage difference error between $T_{p8,25y}$ and commercial codes EED and GLHEPRO remains widely within 10% (in the range between 1.8% and 6.7%). When referring to the 2x2 R configuration the results provided by the three methods (i.e. $T_{p8,25y}$, EED and GLEHPRO) in terms of estimated borehole depth H suggest that the standard 10-year horizon proper of the ASHRAE-T_{p8} method could be sufficient to cover a 30-year life cycle for a correct design of BHE field. This is because, for the 2x2 R configurations, the real g-functions and related $T_{p,g}$ "true" values as evaluated at the 10th and 25th year do not change significantly. As a consequence, the difference in terms of estimated H as evaluated at the 10th and 25th year is negligible for the 2x2 R configurations. For the BHE fields constituted by 10, 16, and 72 boreholes (Rectangular and In-Line configurations), the difference in terms of estimated borehole depth H by the three methods referring to the 10 rather than the 25-year time horizon is higher. Also, the heat load profile and the borehole spacing have a role in the 10 to 25 year overall lengths; if the heat loads are balanced (i.e. the yearly load small compared to its monthly counterpart), or the boreholes are far enough apart and not packed in rectangular configurations, the two lengths move to be similar. In general, moving from 10 to 25 years for the cases under consideration means as an average, an increase of 3.4% on the overall BHE field length, being 5.5% the maximum increase in length based on the adopted input data.

CONCLUSIONS

In the present paper, an updated version of the modified ASHRAE-T_{p8} method has been proposed in order to provide a simple method to correctly design the BHE field for GCHP applications over a 25-year time window. The aim is to offer to the community of technicians and engineers a direct method to be employed in a simple spreadsheet to accurately design the BHE fields with a procedure similar to the one proper of the original ASHRAE method, without needing of disposal of any pre-calculated g-function for each specific configuration. The $T_{p8,25y}$ method incorporates parameters that refer to the 25-year time horizon and new optimized constants that minimize the objective function

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expressing percentage error of the $T_{p8,25y}$ with respect to the reference g-function $T_{p,g}$ "true" values; 135 R and 165 non-R BHE field configurations have been analyzed, also in terms of dimensionless BHE inter distance B/H. For the validation of the robustness of the $T_{p8,25y}$ method for extended time horizons (i.e. 25 years), typical European building structures and related monthly and peak heat loads have been considered. The results in terms of estimated borehole depth H exhibit a percentage difference error related to the $T_{p8,25y}$ in the range 1.8 - 6.7% with respect to EED and 2.8 - 5.5% with respect to GLHEPRO commercial codes covering the same time window of 301 months.

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NOMENCLATURE

α		thermal diffusivity [m²/s]
B	=	BHE spacing [m]
E_1	=	exponential integral in ILS model [-]
Fo	=	Fourier number, $Fo=\alpha\tau/x^2$ [-]
G	=	temperature transfer function in ICS model [-]
g	=	dimensionless (multi BHE) temperature transfer function [-]
H	=	BHE depth [m]/height if referred to the structure/building [m]
k	=	Thermal conductivity [W/mK]
L	=	overall BHEs length [m]
N	=	number of boreholes
π		pi constant [-]
$\dot{Q}$	=	Heat rate [W]
r	=	Radial distance/radius [m]
R	=	thermal resistance [mK/W]
T	=	Temperature [°C]
T_p	=	temperature penalty [°C]
τ		time [s]
θ_8		excess temperature, equation (3) [°C]

Subscripts

ave	=	average value
b	=	borehole
f	=	fluid
gr	=	ground
H	=	based on BHE depth
h	=	referred to 6 hours

m = referred to 1 month

n = referred to 25 years (or 10 years)+1 month+6 hours

ref = reference length (100 m)

tot = total

T_{p8} = referred to the T_{p8} method

y = referred to 25 years (or 10 years)

∞ = undisturbed and initial condition

REFERENCES

Ahmadfard, M. and M. Bernier, 2018. Modifications to ASHRAE's sizing method for vertical ground heat exchangers, Sci Technol Built Environ. 24: 803–817. https://doi.org/10.1080/23744731.2018.1423816.

Ahmadfard, M. and M. Bernier, 2014. An alternative to ASHRAE's design length equation for sizing borehole heat exchangers, Seattle.

Ashrae Handbook-HVAC Applications: Geothermal Energy, ASHRAE, Atlanta, 2015.

Bernier, M, 2006. Closed-Loop Ground-Coupled Heat Pump Systems, ASHRAE J: 12–19.

Carslaw, H.S. and J.C. Jaeger, 1959. Conduction of heat in solids, 2nd Edition, Oxford University Press, Oxford.

Cimmino, M. and M. Bernier, 2014. A semi-analytical method to generate g-functions for geothermal bore fields, Int J Heat Mass Transf. 70: 641–650. https://doi.org/10.1016/j.ijheatmasstransfer.2013.11.037.

Cullin, J.R., Spitler, J.D., and C. Montagud, 2015. Validation of vertical ground heat exchanger design methodologies. Sci. Technol. Built Environ., 21, 137–149. [Google Scholar] [CrossRef]

Cullin, J.R. and J.D. Spitler, 2011. A computationally efficient hybrid time step methodology for simulation of ground heat exchangers, Geothermics. 40: 144–156. https://doi.org/10.1016/j.geothermics.2011.01.001.

EnergyPlus, (n.d.). https://energyplus.net (accessed September 26, 2023).

Eskilson, P, 1987. Thermal analysis of heat extraction boreholes, PhD Thesis, Lund University of Technology.

Fossa, M, 2011. The temperature penalty approach to the design of borehole heat exchangers for heat pump applications, Energy Build. 43 (2011) 1473–1479. https://doi.org/10.1016/j.enbuild.2011.02.020

Fossa, M, 2017. Correct design of vertical borehole heat exchanger systems through the improvement of the ASHRAE method, Sci Technol Built Environ. 23: 1080–1089. https://doi.org/10.1080/23744731.2016.1208537

Fossa, M., Morchio, S., Priarone, A. and S.Memme, 2023. Accurate design of BHE fields for geothermal heat pump systems: the ASHRAE-Tp8 method compared to non aggregated schemes applied to different European test cases, Energy and Buildings.

Fossa, M. and D. Rolando, 2015. Improving the Ashrae method for vertical geothermal borefield design, Energy Build. 93: 315–323. https://doi.org/10.1016/j.enbuild.2015.02.008.

GeoSensingDesign.org, (n.d.). https://www.geosensingdesign.org/ (accessed September 28, 2023).

Hellström, G. and B. Sanner, 1994. Earth Energy Designer: Software for Dimensioning of Deep Boreholes for Heat Extraction.

Ingersoll, L.R., Zobel, O.J. and A.C. Ingersoll, 1954. Heat conduction with engineering, geological, and other applications, McGraw-Hill, New York.

Kavanaugh, S.P. and K. Rafferty, 1997. Ground-Source Heat Pumps: Design of Geothermal Systems for Commercial and Institutional Buildings, in: ASHRAE, Atlanta, Georgia.

Kurevija, T., Vulin, D., and V. Krapec, 2012. Effect of borehole array geometry and thermal interferences on ground source heat pump system. Energy Convers. Manag.: 60, 134–142. [Google Scholar] [CrossRef]

Lamarche, L. 2023. Fundamentals of Geothermal Heat Pump Systems, 1st Edition, Springer Cham, XIII, 295. https://link.springer.com/book/10.1007/978-3-031-32176-4

Rybach, L. and B. Sanner, 1999. Ground-source heat pump systems – the European experience. In: Proc. International, Geothermal Days – Oregon Inst. Of Technology. vol. 1. Klamath Falls/USA; p. 159–70.

Rybach, L. and W.J. Eugster, 2002. Sustainability aspects of geothermal heat pumps. In: Proc. 27th workshop on geothermal reservoir engineering, Stanford University, USA; January 28–30. p. 1–6 [SGP-TR-171].

Spitler, J.D., 2000. GLHEPRO-a design tool for commercial building ground loop heat exchangers, in: Proc. of 4th Int. Heat Pumps in Cold Climates Conference, Aylmer, Quebec.

DOI: https://doi.org/10.22488/okstate.24.000005

Staiti, M., 2014. The Sizing of Borehole Heat Exchangers for Ground Source Heat Pumps: A Comparison Between Two Methods. Master's Thesis, Politecnico di Milano, Milan, Italy. [Google Scholar]

TABULA WebTool, (n.d.). https://webtool.building-typology.eu/#bm (accessed September 26, 2023).

UNI 11466, 2012. Heat pump geothermal systems Design and sizing requirements, page 107, Italian guidelines.

Yavuzturk, C. and J.D. Spitler, 1999. A short time step response factor model for vertical ground loop heat exchangers, in: ASHRAE Transactions 105: pp. 475–485.

Zhang, X., Zhang, T., Li, B., and Y. Jiang, 2019. Comparison of Four Methods for Borehole Heat Exchanger Sizing Subject to Thermal Response Test Parameter Estimation. Energies, 12, 4067. https://doi.org/10.3390/en12214067

Zhi, C., Yang, X., Zhou, X., Tu, S. and X. Zhang, 2022. A revised sizing method for borehole heat exchangers in the Chinese national standard based on reliability and economy, Renewable Energy, Volume 191, Pages 17-29, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2022.04.043

DOI: https://doi.org/10.22488/okstate.24.000005