Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

A Web Application for Geothermal Borefield Design

Davide Rolando[1,2], José Acuna[1] and Marco Fossa[2]

[1]KTH Royal Institute of Technology, Brinellvägen 68, 100 44 Stockholm, Sweden

[2]University of Genova, Via all'Opera Pia 15a, 161 45 Genova, Italy

marco.fossa@unige.it, drolando@kth.se

Keywords: ground coupled heat pumps, borehole heat exchangers, g-functions, thermal response test, web application

ABSTRACT

The correct design of a borehole heat exchanger (BHE) system implies the accurate knowledge of borehole and ground thermal properties, the correct evaluation of building heating or cooling demands and the correct procedure to assess the final overall BHE length related to BHE configuration shape. A careful design is required to make profitable payback plans and provide expected long time performance.

In this paper the principle and description of a web-based suite of tools for BHE design is presented. The web application intends to implement some of the main procedures universally adopted in BHE system design. A section of the present paper describes the implementation of an improved ASHRAE method which allows the BHE system to be designed by considering three representative building heat loads, their respective thermal resistances based on ICS model and a temperature penalty variable which takes into account the long term BHE interaction effect. A new hybrid implementation of the Ashrae method based on g-function calculation is also described for arbitrary borehole field configuration design. This arbitrary shaped borefield design allows the designer to fit the peculiar needs of each application project. Current free or commercial programs allow the user to design BHE systems according to a priori determined set of available configurations in terms of borefield shape and borehole to borehole distances while real applications often require the borehole field geometry not to respect a regular matrix configuration. A further section describes a toolkit for Thermal Response Test (TRT) analysis which allows the estimation of BHE and ground thermal properties. This toolkit provides also a method for the evaluation of the error related to TRT analysis results. Furthermore, a section for analytical estimation of borehole thermal resistance based on literature review is also presented.

1. INTRODUCTION

Ground source heat pumps (GSHP) are widely considered as being among the most energy efficient solution for building space heating and cooling due to their efficiency and reduced maintenance cost compared to conventional HVAC systems.

The borefield design goal is the definition of the best BHE geometry and the optimum overall length and location of vertical and/or inclined boreholes. The constraints of the problem and its input information are the thermal energy demand of the building over time, the ground and BHE thermal properties and a target heat pump performance.

To describe and predict the heat transfer due to the interaction between a BHE field and the surrounding ground, the assumptions of pure heat conduction and homogeneous ground properties are widely adopted. Under those hypotheses some base solutions are available and mainly differ depending on whether the BHE is considered as an Infinite Line Source (ILS), an Infinite Cylindrical Source (ICS) or a Finite Line Source (FLS). The most popular solutions, called temperature response factors, are ILS (Ingersoll et al., 1954) and ICS (Carslaw and Jaeger, 1947). The ILS model was first proposed by Lord Kelvin and is based on the approximation of the BHE heat source as in infinitely long line buried in an infinite volume of ground. The ICS model considers a constant heat transfer rate applied to a cylindrical surface of finite radius and infinite length. Both solutions allow the temperature distribution in the ground to be evaluated in terms of a dimensionless time and radius from the source axis.

The temperature response factor approach was extended by Eskilson (1987) to the description of complex BHE configurations, constituted by finite heat sources positioned in regular arrangements. This approach is based on the proper superposition in space of the numerical solution of the single and FLS problem. The related non-dimensional temperature response factors are known as g-function(s). Analytical studies of the FLS problem have also been developed more recently by Zeng et al. (2004), Lamarche and Beauchamp (2007) and Javed and Claesson (2011).

A number of procedures for designing of BHE field have been suggested and are currently implemented in computer programs. Kavanaugh and Rafferty (1997) proposed a method that has been recommended by the American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) and is used in their own ground loop design software. Eskilson (1986, 1987) proposed a method which later has been partially implemented in the "Earth Energy Designer (EED)" software by the Department of Mathematical Physics (Lund University, Sweden) and the Institute of Applied Geosciences (Justus-Liebig-University, Germany), as described by Hellström and Sanner (1997). Likewise, the computer program GLHEPRO is a well-known tool for borefield design, proposed by Marshall and Spitler (1994), and developed at Oklahoma State University.

The Ashrae method allows the BHE system to be designed by considering three representative building heat loads, their respective thermal resistances based on ICS model and a temperature penalty variable which takes into account the long term BHE interaction effect. The strength of this method is its simplicity. The design of the BHE field, in terms of BHE overall length, can be easily performed without a dedicated computer as those based on monthly or hourly description of the building heat load profiles (Hellström and Sanner, 2001 and Spitler et al., 2009).

In the method proposed by Eskilson (1987) the temperature response factors (called g-functions) are evaluated numerically by spatial superposition of the FLS solution. The g-function values are then employed in a temporal superposition algorithm depending on the monthly building heat load profile per BHE unit length, the ground thermal properties and the borehole geometrical and thermal characteristics. As a result, the overall BHE length required can be evaluated. The implementation of this method in the commercial software EED and GLHEPRO is based on using a finite number of pre-calculated g-function values stored in a dedicated database and related to respective BHE configurations. One of the limitations of this approach is related to the finite range of BHE configurations available. The g-function related to an arbitrary BHE configuration can be evaluated according to approaches proposed by Zeng et al. (2004), Lamarche and Beauchamp (2007) and Javed and Claesson (2011) but the calculation is currently too computationally demanding. An approximation of the FLS solution has been recently proposed by Fossa and Rolando (2014b), which allows fast calculations of temperature response factor of complex BHE fields. With this approach the generation of thermal response factor for arbitrary BHE arrangements is possible with low computational demand.

In all design methods for sizing the boreholes for ground-source heat pump systems, the ground and BHE thermal properties are very important parameters that can lead to an erroneous estimate of the required overall borehole length. The evaluation of borehole effective thermal resistance and effective ground thermal conductivity can be assessed by means of a Thermal Response Test (TRT). The TRT is a worldwide adopted in-situ methodology based on heat rate injection (extraction) to (from) the ground through a fluid circulating in a pilot BHE. The measured fluid temperature evolution recorded during the test is analyzed with numerical or analytical approaches based on the above mentioned models in order to evaluate the parameters of interest. This measurement procedure was first used by Mogensen (1983) and it is based on the ILS model. ILS is able to describe the thermal response of an infinite ground medium. TRTs are based on constantly heating (or cooling) a fluid circulated through a BHE while measurements of inlet and outlet fluid temperature versus time allow the estimation of the average thermal conductivity of the ground (k) together with the effective borehole resistance (R_{bhe}). The first measurement device designed and built by Mogensen (1983) was based on a chiller to perform a TRT in cooling mode. Later, other mobile measurement devices were introduced mainly in Sweden, USA and Netherlands for both heating (Eklöf and Gehlin, 1996, Austin, 1998) and cooling (Van Gelder et al., 1999) TRT purposes. More recently, an extended TRT measurement technique named Distributed Thermal Response Test (DTRT) has been introduced by Fujii at al. (2006) and Acuña et al. (2009), to allow a more detailed description of the ground and BHE thermal properties.

Even though the theoretical background and laboratory application of the line source solution for thermal conductivity evaluation has been well known since long ago, Niven (1905) and Stålhane et al. (1931), the uncertainty related to ground test measurements has not been studied with sufficient attention and is often missing in current TRT evaluation procedures. An extensive study of this problem has been presented by Witte (2013) in order to describe some solutions and methods to take into account the sources of uncertainty involved in TRT experiments and evaluate their effects on the quality of a TRT result.

The borehole thermal resistance can also be determined by means of analytical and numerical models. All those models propose to decompose R_{bhe} into three contributions: grout conductive resistance (when grouting is applied), pipe conductive resistance and fluid convective resistance. One of the first models is the Gu and O'Neal (1998) equivalent diameter method, a very simple approach based only on the diameter of the U-pipe and the center to center distance between the two pipe legs. Another method, by Paul (1996), was created using both experimental data and numerical results. Other expressions for the borehole resistance have been given by Bennet et al. (1987), Hellström (1991), Diao et al. (2004) and Sharqawy (2009). A recent work of Lamarche et al. (2010) extensively compares these models by means of finite element numerical simulations.

In this paper a web application for studying and designing of BHEs fields is presented. The application uses many of the methods mentioned above and it is organized in different toolkits related to fundamental steps involved in BHE field design. A flowchart is shown in the appendix section. Each toolkit is based on one or more calculation procedures described in this paper together with the user input settings as well as the output results. First, the borefield design procedure is considered. The implementation of the improved Ashrae method is described and the procedure for the temperature penalty evaluation as suggested by Fossa and Rolando (2014a) is presented together with a new hybrid Ashrae method which allows the designing of arbitrary shaped BHE field. A toolkit for TRT analysis is also described and finally a section related to the implemented expressions suitable for R_{bhe} evaluation is discussed.

2. BOREFIELD DESIGN

The present web application implements the improved Ashrae method and a new hybrid Ashrae method briefly described below. A step by step interface drives the user through the settings of the required input parameters and the choice of the design mode. For the sake of brevity the details of the graphic user interface is intentionally neglected here and the following description focuses on the implemented logic and algorithm.

2.1 Improved Ashrae Method

The Ashrae method (Kavanaugh and Rafferty, 1997) is one of the few engineering models that allows a system Borehole Heat Exchanger (BHE) to be designed quickly, 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 is the evaluation of the Temperature Penalty correction T_p, which takes into account the long term thermal interactions of neighbor boreholes. The final formula for BHE field design can be written according to the following expression:

$$L = \frac{\left\{\dot{Q}_y R_y + \dot{Q}_m R_m + \dot{Q}_h \left(R_h + R_{bhe}\right)\right\}}{T_{gr,\infty} - T_{f,ave}(\tau_N) - T_p} \tag{1}$$

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 thermal resistance of the BHE that can be estimated by a thermal response test or suitable formulas (see sections 3 and 4).

The three reference times involved in the calculation can be defined as:

$$\tau_1 = 10\, years \qquad \tau_2 = \tau_1 + 1\, month \qquad \tau_N = \tau_2 + 6\, hours \tag{2}$$

The T_p term is the temperature penalty is introduced in the Ashrae standard as the "penalty for interference of adjacent bores".

It has been demonstrated that the original Ashrae T_p evaluation method leads to an underestimation of the BHE overall length. The error increases the larger the borefield is. A new method has been proposed by Fossa and Rolando (2014a) to assure more accurate results in terms of overall BHE length. The improved temperature penalty evaluation, implemented in the web application, is described briefly here.

2.1.1 Temperature penalty evaluation

According to the improved method, the T_p can be expressed as:

$$T_p = \theta_8 \frac{aN_4 + bN_3 + cN_2 + dN_1}{N_{tot}} \tag{3}$$

where N_4, N_3, N_2 and N_1 are the number of boreholes surrounded by "only" 4 neighbor boreholes, only 3, and so on, respectively. As an example for clarifying the criterion, a rectangular borefield constituted by 3×4 BHEs has N_4=2, N_3=6, N_2=4, N_1=0, N_{tot}=12, while an in-line configuration 4×1 has N_4=0, N_3=0, N_2=2, N_1=2.

The term θ_8 can be expressed as:

$$\theta_8 = \dot{Q}'_y \frac{E_1(\tau_N, B) + E_1(\tau_N, B\sqrt{2})}{\pi k L} \tag{4}$$

where B is the center to center distance between boreholes, k is the ground thermal conductivity and E_1 is the exponential integral (the "core" of the ILS solution), that can be for example approximated as an expansion series in terms of the $1/4Fo_r$ variable, being Fo_r the Fourier number based on BHE radius r_b.

2.1.2 User input and design mode

The inputs requested are the building monthly thermal loads, the heat pump characteristics, the BHE geometric and thermal properties, the ground thermal properties and the desired BHE configuration. The heat pump characteristics required by the Ashrae method are: seasonal average coefficient of performance (COP) for heating and cooling mode, COP for peak heating and cooling modes, inlet and outlet working fluid temperature limits for heating and cooling mode. The ground thermal properties requested are: undisturbed ground temperature, ground thermal conductivity and ground thermal diffusivity. The borehole characteristics required involve both geometrical and thermal properties. From the geometrical point of view the BHE is identified by its radius. Optional values are used according to different design mode and include minimum and maximum BHE length. The BHE effective thermal resistance is required for the calculation and, if not available, can be evaluated by means of a dedicated tool, as described in Section 4 (it is important to keep in mind that this resistance is not the same for all boreholes in the same system, but this is a typical assumption in this type of design approach). The desired BHE configuration can be set by specifying the overall number of boreholes in terms of borehole number and spacing, configuration type (rectangular, inline, L-shape, U-shape, O-shape) and BHE center to center distance.

Figure 1 shows a detail of the graphic user interface for the settings of input parameters related to the heat pump characteristics. For each input a dedicated parameter control assures that the settings are within respective range limits and consistent with the calculation procedure. Required field are marked and default settings are provided. In the appendix section, Figure 2a shows the flowchart related to the Ashrae method implementation.

Table 1: User input for improved Ashrae method implementation.

INPUT	MODE	OUTPUT
Initial borefield configuration type (rectangular, inline, L-shape, U-shape or open rectangle) HP characteristics BHE type BHE thermal properties Ground thermal properties	Mode A: the user sets a fixed returning temperature and a maximum value of borehole depth. Mode B: the user sets a fixed borehole depth and a minimum returning fluid temperature.	Final borefield configuration Overall BHE length

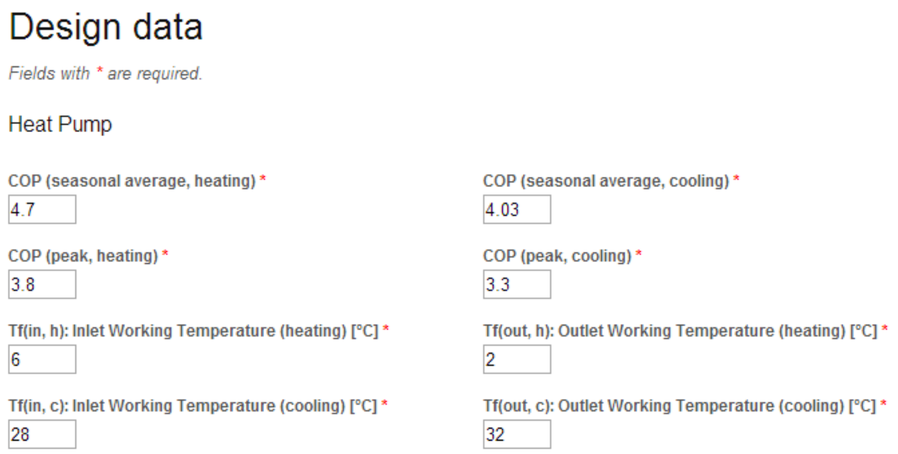

Figure 1: Detail of the input user interface related to Ashrae method implementation.

The user can choose two different design modes according to different sets of design constraints. In one case (Mode A) the user is requested to select a preferred borehole configuration type (among rectangular, inline, L-shape, U-shape and O-shape) and initial borehole number and spacing, the returning fluid temperature to the heat pump and a maximum value for the borehole depth. The algorithm implemented returns the overall BHE length L and the borefield geometry which fulfil the selected inputs.

The second design mode (Mode B) consists again in the user choice of an initial value of borehole configuration. The second input constraint is a fixed value of the borehole depth and a minimum value of the returning fluid. By means of an automatic iterative procedure, the related optimal borehole configuration size is evaluated.

2.1 Hybrid Ashrae Method

One of the main restrictions of the Ashrae method (either the original or the improved one) is the impossibility for it to be employed for arbitrary BHE configuration design. The temperature penalty approach can only be applied for regular matrixes and this is often a big limitation for real case applications. Also, most commercial software design procedures are based on pre-calculated values of g-functions stored in a database, limiting the set of available BHE configurations in terms of borefield shape and borehole to borehole distances.

The g-function related to an arbitrary BHE configuration can be evaluated according to different approaches but the calculation is currently too computationally demanding. Fossa and Rolando (2014b) proposed an Approximated Finite line Source Solution (AFSS) which employs the FLS solution and is suitable for fast spatial and temporal superposition. With this approach the generation of thermal response factor for arbitrary BHE arrangements is possible with low computational demand. The AFSS approach is based on the following expressions:

$$T_{ave}(r)-T_{gr,\infty}=\frac{\dot{Q}'}{2\pi k_{gr}}\left\{a_1\left\{-\gamma+\ln\left[a_2\left(\frac{r}{H}\right)^{-2}Fo_H\right]+a_3\frac{r}{H}+\frac{a_4}{\sqrt{\pi}}\left(\sqrt{a_5\,Fo_H}+\left(\frac{r}{H}\right)^2\sqrt{\frac{1}{4\,Fo_H}}\right)\right\}\right\} \tag{5}$$

$$T_{ave}(r)-T_{gr,\infty}=\frac{\dot{Q}'}{2\pi k_{gr}}\left\{a_6\left(a_7+a_8\ln\left(\frac{r}{H}\right)+a_9\frac{r}{H}+a_{10}\left(\frac{r}{H}\right)^2+\frac{1}{a_{11}\sqrt{\pi}}\left(\frac{1}{Fo_H}\right)^{a_{12}}\right)\right\} \tag{6}$$

where γ is the Euler constant and Fo_H is the Fourier number based on BHE length H. The constants $a_1 ... a_{12}$ have been derived by means of an optimum search procedure. The reader is referred to the work of Fossa and Rolando (2014b) for a detailed description of Eq. (7-8) and the constant refinement procedure.

The temperature penalty variable introduced in the Ashrae method has been demonstrated to be related to the error introduced by calculating the ground thermal resistance (Eq.4) by means of the ICS solution with respect to the proper g-function for the borefield under consideration (Fossa, 2011).

For the design of arbitrary shaped BHE field the web application presented in this paper implements a modified hybrid Ashrae procedure which does not require by definition the temperature penalty evaluation and considers a new expression for the ground thermal resistance related to the long term period. Eq.(1) becomes:

$$L=\frac{\left\{\dot{Q}_y\,\mathrm{R}_{y,AFSS}+\dot{Q}_m\,R_m+\dot{Q}_h\left(R_h+R_{bhe}\right)\right\}}{T_{gr,\infty}-T_{f,ave}(\tau_N)} \tag{7}$$

where $R_{y,AFSS}$ is defined as:

$$R_{y,AFSS} = \frac{g(\tau_N)_{AFSS} - g(\tau_1)_{AFSS}}{k} \quad (8)$$

where $g(\tau)_{AFSS}$ is the FLS response factor evaluated at a given Fourier number and obtained by spatial superposition of the AFSS formulation shown in Eq.(7-8).

With this approach, the same procedure described in the previous paragraph can be employed to design arbitrary BHE fields. The implementation of this algorithm allows the presented Web Application to be employed for fast design of BHE systems that are not ascribed to regular matrixes pattern. For real case applications this represents a fundamental advantage over most typical design procedures and popular computer software.

3. THERMAL RESPONSE TEST

In all design methods for ground source heat pump borefields, the ground thermal properties and the thermal properties of the borehole are essential input parameters. These parameters can be estimated by means of theoretical and empirical expressions.

The variable that rules the heat conduction process into the ground is the thermal diffusivity, which involves the ground thermal conductivity and the ground heat capacity. A review of tables of ground thermal properties reveals significant variability in values depending on different author results, even when the same geological type is considered (Banks, 2008). Ground thermal conductivity can normally vary in the range 1 to 5 [W/m/K] with recurring values between 2 and 3. On the other hand the ground heat capacity average value is typically around 2[MJ/m^3/K] varying in most cases from 1.6 to 2.4[MJ/m^3/K]. Table 2 reports the results of the design of a single borehole system according to ground thermal conductivity and ground heat capacity values. Inspection of the table makes apparent the primary role played by the ground conductivity on the required overall borehole length and hence the necessity of reliable estimations of this quantity.

Table 2: Results of sensitivity analysis on required length for a single borehole configuration. Borehole length is reported according to variability range limits of ground thermal conductivity and heat capacity

k [W/m/K]	C [MJ/m^3/K]	L [m]	ΔL
1	2	152.3	≈86%
5	2	60.3	
3	**1.6**	83.3	≈1.8%
3	**2.4**	81.8	

The TRT is often carried out following the ASHRAE recommendations. First, the undisturbed ground temperature is measured. Then a constant heat load is supplied (or extracted) to the heat carrier fluid through electrical resistances (or by a chiller unit). The fluid inlet, outlet and ambient temperatures (T_{in}, T_{out}, T_{amb}), the mass flow rate $\dot{m}$ and electrical power $\dot{Q}_{el}$ are measured and recorded at given time intervals. The heat rate per borehole length can be determined by:

$$\dot{Q}' = \frac{\dot{m}c(T_{in} - T_{out})}{H} \quad (9)$$

where c is the fluid specific heat and H is the borehole length (BHE depth). The result of this calculation can be compared to the electric power if an electric heater is used to supply heat.

3.1 Thermal Response Test Analysis

The analysis of the TRT data is usually based on the ILS model, where an infinite long linear source is delivering to the ground a constant thermal power per unit length.

According to this model the temperature field in the radial direction r after a time τ elapsed from heat injection (or extraction) start is given as:

$$T(r,\tau) - T_{gr,\infty} = \frac{\dot{Q}'}{4\pi k}\int_{\frac{r^2}{4\alpha\tau}}^{\infty} \frac{e^{-u}}{u} du = \frac{\dot{Q}'}{4\pi k} E_1\left(\frac{r^2}{4\alpha\tau}\right) \quad (10)$$

where $T_{gr,\infty}$ is the undisturbed ground temperature and α is the gound thermal diffusivity.

Of practical interest is the evaluation of the ground temperature at the BHE wall, say for $r=r_{bhe}$. Hence, considering the exponential integral (E_1) approximation as proposed by Abramovitz and Stegun (1964), the temperature at borehole wall can be calculated as:

$$T(r_{bhe},\tau) = T_b = \frac{\dot{Q}'}{4\pi k}\left(ln\left(\frac{4\alpha\tau}{r_{bhe}^2}\right) - \gamma\right) + T_{gr,\infty} \quad (11)$$

The thermal characteristics of a BHE are determined by its effective thermal resistance R^*_{bhe} which is defined in terms of the temperature difference of the fluid (T_f) and the borehole wall (T_b) as:

$$R^*_{bhe} = \frac{T_f - T_b}{\dot{Q}'} \quad (12)$$

The effective borehole thermal resistance in particular is referred at the "surface" fluid temperature difference (say evaluated at BHE top) and it indirectly takes into account the geometrical, thermal and fluid-dynamic parameters aspects of the BHE accounting for the thermal shunt between down and up going fluid. The lower is the borehole resistance the higher is the quality of the BHE itself.

Thus, the fluid temperature as a function of time can be written as:

$$T_f(\tau) = \frac{\dot{Q}'}{4\pi k}\left(ln\left(\frac{4\alpha\tau}{r_{bhe}^2}\right) - \gamma\right) + \dot{Q}' \cdot R_{bhe}^* + T_{gr,\infty} \tag{13}$$

In this model T_f corresponds to the average between the inlet and outlet fluid temperatures.

If $\dot{Q}$ is constant, the Eq. (13) becomes a simple linear expression with respect to the logarithm of time:

$$T_f(\tau) = S \cdot \ln(\tau) + I \tag{14}$$

where the slope S and intercept I are quantities related to ground thermal conductivity k and to R_{bhe}^* respectively.

As suggested by Eq.(14) an estimation of the slope S and intercept I is possible through a (log)linear regression.

The ground thermal conductivity and effective borehole thermal resistance can hence be evaluated according to the expressions (15) and (16):

$$k = \frac{\dot{Q}'}{4\pi S} \tag{15}$$

$$R_{bhe}^* = \frac{1}{\dot{Q}'}\left(I - T_{gr,\infty} - \frac{\dot{Q}'}{4\pi k}\left(ln\left(\frac{4\alpha}{r_{bhe}^2}\right) - \gamma\right)\right) \tag{16}$$

3.1.1 Distributed TRT

Ordinary TRT procedure is based on BHE inlet and outlet temperature measurements right outside the ground and the arithmetic average temperature considered in TRT analysis is assumed constant along the BHE.

In a Distributed thermal response test (DTRT) the ground thermal conductivity and borehole thermal resistance are determined at many instances along the depth. Distributed temperature measurement can be carried out using various equipment, but a convenient technique is the use of a fiber optic cable. It is normally recommended to perform the measurements during the following three phases: undisturbed ground conditions, constant heat injection (or heat extraction) and borehole thermal recovery.

A first application of DTRT has been done by Fujii at al. (2006) with an optical fiber cable installed on the external wall of the pipe, hence without the opportunity to evaluate the borehole thermal resistance. More recently Acuna et al. (2009) performed a number of DTRT experiments with fiber optic cable located inside a U-BHE pipe, giving the possibility to evaluate both ground thermal conductivity and borehole thermal resistance of a number of ground layers.

The first phase of a DTRT (undisturbed conditions) gives a precise picture of the temperature profile along the depth. This profile has been proven to be rather local and dependent on a number of factors. Many TRT providers have started to include temperature loggings before their tests by slowly submersing a point sensor and subsequently taking it up. The latter can take up to a couple of hours and does not allow a check of the repeatability of the measured values. A logging with fiber optics integrates instantaneously along the whole depth and enables a determination of the random temperature error with several repetitions that do not require any man-hours.

Because the undisturbed temperature profile is measured accurately at the first phase, the pre-circulation phase loses its importance. This phase is, however, recommended in order to ensure a stable fluid circulation as air bubbles may take some time to be released from the system.

The heat injection or heat extraction phase is used to disturb the borehole during a convenient period, long enough to calculate the borehole resistance (if necessary). The comparison of the rate at which different borehole sections are heated or cooled gives an indication of high or low conductive layers.

The thermal recovery period is used to calculate the ground thermal conductivity along the depth. The latter period is characterized by the absence of a radial temperature gradients in the borehole, thereby eliminating any systematic temperature uncertainties due to the position of the fiber cable inside the borehole (as is the case for the heating or cooling period), i.e. resulting in more accurate thermal conductivity values. The thermal conductivities found here are used as inputs in case the borehole resistance is to be calculated using the data from the heating/cooling phase.

The procedure to mathematically analyze the measured data at each section along the depth is the same as for conventional TRTs, e.g. Eq. (10).

3.1.2 TRT and DTRT analysis: user input and output

The web application described in this paper provides a toolkit for TRT and DTRT measurement analysis. DTRT section is being built but the basic algorithm structure has already being implemented.

TRT and DTRT equipment typically include a data logger device which saves the measurements of interest in a log file. This file is usually a text document where data are organized in a raw grid format with as many columns as the number of parameters measured. Each row is appended to the log file at preset time intervals and contains the measurement of every parameter at a given time. Each data logger typically has a log file format that may differ slightly from other devices depending on many details, such as the column order and the column separator character. A tool for importing a number of TRT log file formats is provided in the web application, but for the sake of brevity this is not described further here.

For both TRT and DTRT the user can select an arbitrary data range to be considered for the calculation. In particular, for DTRT analysis, a proper user form is shown to give the possibility to select the sections to be considered in the analysis.

3.2 Uncertainty Analysis

Many variables are repeatedly measured during a TRT (by means of temperature sensors, flow sensors and power meters). The undisturbed ground temperature is measured before the test. Some input are estimated independently (e.g.: ground density, ground volumetric heat capacity). Each measurement introduces an error which affects the final estimation of the thermal conductivity and the borehole thermal resistance. Current TRT reports often lack an estimation of the quality of the calculated results, bringing an unknown uncertainty to the result of a BHE field design.

Witte (2013) presented an extensive study of the uncertainty sources to be considered for evaluating the quality of a TRT results and proposed a method to calculate the overall error related to ground conductivity and borehole resistance estimation. The method takes into account the uncertainty sources summarized in Table 3.

Table 3: TRT uncertainty sources (Witte, 2013)

$\dot{m}$	Heat carrier mass flow	ΔT	Temperature difference
C_f	Heat carrier heat capacity	r_b	Borehole radius
T_{in}	Injection fluid temperature	H	Borehole depth
T_{out}	Return fluid temperature	C	Ground heat capacity
T_g	Undisturbed ground temperature	S	Regression slope coefficient

For each uncertainty source the related individual uncertainty value can be evaluated. As an example, the error in the calculated temperature difference (i.e.: $\delta\Delta T$) depends on the combination of the errors related to individual sensors (i.e.: δT_{in}, δT_{out}). This can be evaluated as:

$$\delta\Delta T = \sqrt{(\delta T_{in})^2 + (\delta T_{out})^2} \tag{17}$$

The error of the final result depends on how all individual errors affect the final error. Error propagation in the web application is calculated using the general procedures as outlined by Taylor (1997) and Ellison et al. (2000). The final expressions for TRT results uncertainty evaluation are implemented as:

$$\delta k = k\sqrt{\left(\frac{\delta\dot{m}}{\dot{m}}\right)^2 + \left(\frac{\delta c}{c}\right)^2 + \left(\frac{\delta S}{S}\right)^2 + \left(\frac{\delta\Delta T}{\Delta T}\right)^2 + \left(\frac{\delta H}{H}\right)^2} \tag{18}$$

$$\delta R_{bhe} = \sqrt{\left(\frac{\Delta R_{bhe}}{\Delta H}\delta H\right)^2 + \left(\frac{\Delta R_{bhe}}{\Delta\dot{Q}}\delta\dot{Q}\right)^2 + \left(\frac{\Delta R_{bhe}}{\Delta I}\delta I\right)^2 + \left(\frac{\Delta R_{bhe}}{\Delta T_g}\delta T_g\right)^2 + \left(\frac{\Delta R_{bhe}}{\Delta k}\delta k\right)^2 + \left(\frac{\Delta R_{bhe}}{\Delta C}\delta C\right)^2 + \left(\frac{\Delta R_{bhe}}{\Delta r_b}\delta r_b\right)^2} \tag{19}$$

The web application presented in this paper implements this approach to evaluate the overall uncertainty related to TRT data. A user form is provided to set the individual uncertainty values for the measurement sensors and the input properties.

Table 4 provides a summary of input and output parameters related to thermal response test toolkit. Figure 2b in the appendix section shows the flowchart related to the thermal response test analysis implementation.

Table 4: User input for TRT and DTRT analysis

INPUT	OUTPUT
Logfile columns: (Mandatory measured data) time, circulating fluid flow rate and thermal properties, BHE inlet and outlet temperatures. (Optional) electric power, ambient temperature. Additional input information: Undisturbed ground temperature, ground volumetric heat capacity, BHE radius, BHE length, data range, individual input uncertainties. For DTRT Amount and length of sections to be analyzed should be given and, for each of these, the same inputs named above are necessary. Observe that the undisturbed ground temperature value varies with depth according to the measured profiled in phase 1 of the test.	k R_{bhe} δk δR_{bhe}

4. BOREHOLE THERMAL RESISTANCE

The borehole thermal resistance in grouted boreholes can also be determined by means of numerical and analytical approaches if the geometry is known. All the proposed analytical models decompose R_{bhe} into three contributions: grout conductive resistance (R_{grout}), pipe conductive resistance (R_{cond}) and fluid convective resistance (R_{conv}):

$$R_{bhe} = R_{cond} + R_{conv} + R_{grout} \tag{20}$$

The first two resistances can be expressed as:

$$R_{cond} = \frac{\ln(r_{po}/r_{pi})}{4\pi k_p} \tag{21}$$

$$R_{conv} = \frac{1}{4\pi r_{pi} h} \tag{22}$$

where r_{po} and r_{pi} are respectively the outer and inner pipe radius, k_p is the pipe thermal conductivity and h is the convective heat transfer coefficient. Several correlations for calculating h as a function of the Nusselt number are available in the toolkit. The same applies for different pipe materials and dimensions.

The grout resistance gives the main contribution to the total borehole resistance and is the most difficult to evaluate. Although many approaches of varying complexity have been proposed, the web application presented here implements the following.

A model suitable for evaluating borehole resistance of single U-pipe BHE is the Paul method (1996) which was created using both experimental data and a two-dimensional finite element program for modeling a borehole cross section. Grout thermal resistance is expressed as:

$$R_{grout} = \frac{1}{\beta_0 (r_{bhe}/r_{po})^{\beta_1} k_{grout}} \tag{23}$$

where the coefficients β_0 and β_1 are tabulated for different center to center distance between the two legs of the U-tube (also known as shank spacing), r_{bhe} is the BHE radius and k_{grout} is the grout thermal conductivity.

Further development will also include the multipole approach for single U-tube BHE as proposed by Bennet et al. (1997).

An expression for the calculation of the borehole resistance in symmetrically disposed double U-tubes has been proposed by Hellström (1991):

$$R_{bhe} = \frac{1}{2\pi k_{grout}}\left[ln\left(\frac{r_{bhe}}{r_{po}}\right) - \frac{3}{4} + \left(\frac{\chi_c}{r_{bhe}}\right)^2 - \frac{1}{4}ln\left(1 - \left(\frac{\chi_c}{r_{bhe}}\right)^8\right) - \frac{1}{2}ln\left(\frac{\chi_c\sqrt{2}}{r_{po}}\right) - \frac{1}{4}ln\left(\frac{\chi_c\sqrt{2}}{r_{po}}\right)\right] + \frac{R_{cond}}{4} \tag{24}$$

where χ_c is the shank spacing

Finally, the expressions implemented to evaluate the conductive and grout resistance of a simple coaxial pipe are:

$$R_{cond} = \frac{1}{\pi d_{i,out} h_{i,out}} \frac{1}{2\pi k_{p,out}} ln\left(\frac{d_{o,out}}{d_{i,out}}\right) \tag{25}$$

$$R_{grout} = \frac{1}{2\pi k_{grout}} ln\left(\frac{d_{bhe}}{d_{e,out}}\right) \tag{26}$$

where:

$d_{i,out}$ is the inner diameter of external pipe

$d_{o,out}$ is the outer diameter of external pipe

$h_{i,out}$ is the convective coefficient outside the internal pipe.

$k_{p,out}$ is the thermal conductivity of the external pipe

d_{bhe} is the BHE diameter

Figure 2c in the appendix section shows the flowchart related to the implementation of the toolkit in the web application.

CONCLUSIONS

In this paper the first version of a web application based on a set of fundamental tools for shallow geothermal borefield design is presented. In spite of the fact that work is needed in refining and debugging, further literature comparison on available models, and additional numerical comparisons based on different algorithms, the tool is ready to accomplish the main design goals according to which it was conceived. In this paper in particular the implementation of an improved version of the Ashrae method for borefield design has been described, together with a new hybrid Ashrae method which allows the design of arbitrary borefield configuration. The importance of such feature in real case applications has been remarked. A toolkit for thermal response test analysis has been presented. Because the uncertainty evaluation related to such test measurement is often missing in reports, particular attention has been given in the toolkit to evaluating the result error. The application also contains a module for doing theoretical calculation of the borehole resistance based on a set of recent literature models.

Further development of the web application will include a design analysis and ground response prediction based on a larger set of building heating and cooling loads (e.g. on a monthly basis) and economic and financial indicators to be applied for comparison with traditional heating and cooling plant solution. Every module presented in this paper will be also further developed and updated on the strength of ongoing study results.

APPENDIX

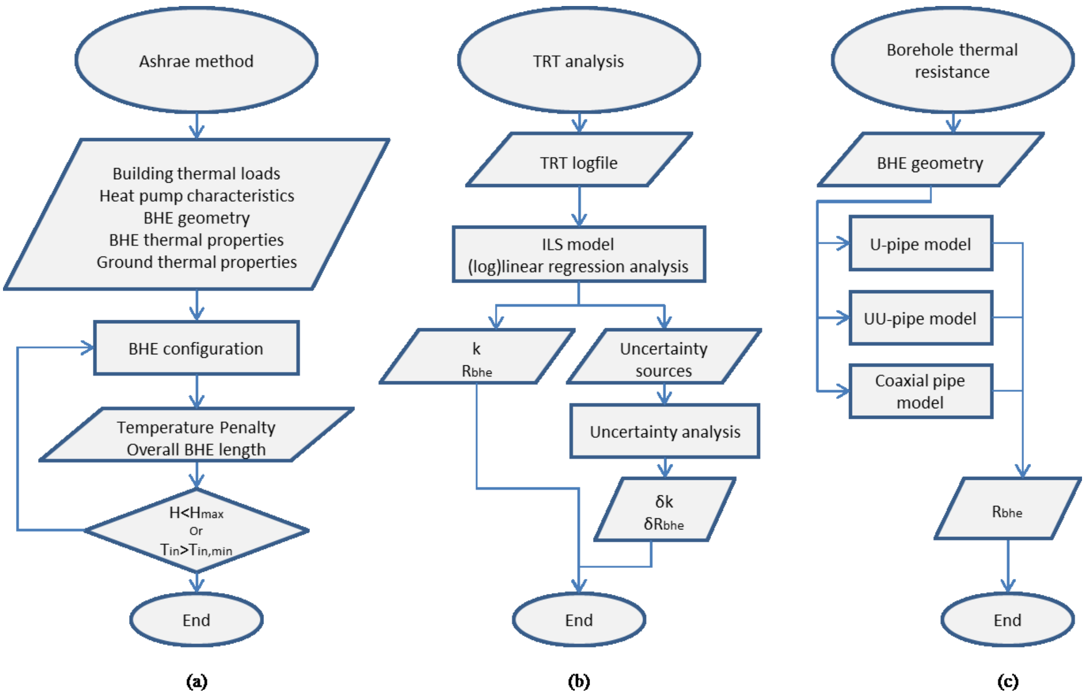

Figure 2: Web Application flow chart

REFERENCES

Abramovitz M. and Stegun I.A., 1964. Handbook of Mathematical Functions With Formulas, Graphs, and Mathematical Tables, NBS Applied Mathematics Series 55, National Bureau of Standards, Washington, DC.

Acuña, J., Mogensen P., Palm, B.: Distributed thermal response test on a U-pipe borehole heat exchanger, *Proceedings*, Effstock-The 11th International Conference on Energy Storage, Stockholm, (2009).

ASHRAE Handbook 2007. *HVAC Systems and Equipment,* (2007).

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

Austin, W.: Development of an in-situ system for measuring ground thermal properties. *MSc-thesis*, OSU, (1998), 164pp.

Banks, D.: An introduction to thermogeology: ground source heating and cooling, *book*, John Wiley & Sons, (2012).

Bennet, J., Claesson J., Hellström G.: Multipole Method to Compute the Conductive Heat Flows to and Between Pipes in a Composite Cylinder, University of Lund, Department of Building Technology and Mathematical Physics. Lund, Sweden, (1987).

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

Claesson, J., and Javed, S.: An Analytical Method to Calculate Borehole Fluid Temperatures for Time-scales from Minutes to Decades. ASHRAE Transactions, 117.2 (2011).

Diao N., Zeng H., Fang Z.: Improvement in modeling of heat transfer in vertical ground heat exchangers, *HVAC&R Research*, 10, (2004), 459 – 470.

Eklöf, C. and Gehlin, S.: TED - A mobile equipment for thermal response test. *MSc-thesis*, LuTH, (1996), 62pp.

Ellison SLR, Williams A.: Quantifying Uncertainty in Analytical Measurement, *Eurachem/CITAC guide*, Third edition, (2012).

Eskilson P.: Superposition Borehole Model. Manual for Computer Code, Dept. of Mathematical Physics, Lund Institute of Technology, Lund, Sweden, (1986).

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., Rolando D.: Improving the Ashrae method for vertical geothermal borefield design, *Proceedings*, IEA Heat Pump Conference, 12-16 May, Montreal (Québec) Canada, (2014a).

Fossa, M., Rolando D.: Fully Analytical Finite Line Source Solution for Fast Calculation of Temperature Response Factors in Geothermal Heat Pump Borefield Design, *Proceedings*, IEA Heat Pump Conference, 12-16 May, Montreal (Québec) Canada, (2014b).

Fuijii H., Okubo H., Itoi R.: Thermal Response Tests Using Optical Fiber Thermometers, Kyushu University, Fukuoka, *GRC Transactions*, 30, (2006).

Gu, Y., and O'Neal, D. L.: Development of an Equivalent Diameter Expression for Vertical U-Tubes Used in Ground-Coupled Heat Pumps, *ASHRAE Transactions*, 104.2, (1998), 347-355.

Hellström, G. and Sanner, B.: EED – Earth Energy Designer, Version 1.0, User's Manual. Prof. Dr. Knoblich & Partner GmbH, Wetzlar, Germany, (1997), 43pp.

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

Hellström, G.: Thermal performance of borehole heat exchangers. Department of Mathematical Physics, Lund Institute of Technology, (1991).

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

Kavanaugh, S.P. and Rafferty, K.: Ground Source Heat Pumps Design of Geothermal System for Commercial and Institutional Buildings, *ASHRAE Conference*, 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.

Lamarche L., Kajl S., Beauchamp B.: A review of methods to evaluate borehole thermal resistances in geothermal heat-pump systems, *Geothermics*, 39, (2010), 187-200.

Marshall, C.L., Spitler, J.D.: GLHEPRO – The Professional Ground Loop heat Exchanger Design Software, User's Guide, (1994).

Mogensen, P.: Fluid to duct wall heat transfer in duct system heat storages, Swedish Council for Building Research, 16, (1983), 652-657.

Niven, C.: On a method of finding the conductivity for heat, *Proceedings of the Royal Society of London*, Series A, Containing Papers of a Mathematical and Physical Character, 76, (1905), 34-48.

Pahud, D., Matthey, B.: Comparison of the thermal performance of double U-pipe borehole heat exchangers measured in situ. *Energy and Buildings*, 33, (2001), 503-507.

Paul N.D.: The Effect of Grout Thermal Conductivity on Vertical Geothermal Heat Exchanger Design and Performance, *Msc-Thesis*, South Dakota State University, (1996).

Sharqawy M.H., Mokheimer, E.M., Badr, H.M.: Effective pipe-to-borehole thermal resistance for vertical ground heat exchangers *Geothermics*, 38, (2009), 271–277.

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).

Spitler, J.D.: GLHEPRO - A design tool for commercial building ground loop heat exchanger. In: Proceedings of the 4th International Conference on Heat Pumps in Cold Climates, 17-18 August, Aylmer, QC, Canada, (2000), 1-16.

Stålhane, B., Pyk, S.: Ny metod för bestämning av värmeledningskoefficienter, *Teknisk Tidskrift*, Svenska Teknologföreningen, 28, (1931).

Taylor JR.: An introduction to error analysis: the study of uncertainties in physical measurements, University Science Books, (1997).

Van Gelder, G., Witte, H.J.L., Kalma, S., Snijders, A. and Wennekes, R.G.A: In-situ-Messung der thermischen Eigenschaften des Untergrunds durch Wärmeentzug, *Proceedings*, OPET-Seminar Erdgekoppelte Wärmepumpen, (1999), 56-58.

Witte, Henk JL.: Error analysis of thermal response tests, *Applied Energy*, 109, (2013), 302-311.

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.