A TRNSYS assisting tool for the estimation of ground thermal properties applied to TRT (thermal response test) data: B2G model

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Abstract:

The determination of ground thermal properties is essential to design competitive commercial ground source heat pump systems. A thermal response test (TRT) carried out on site allows the determination of both the conductivity of the ground and the borehole thermal resistance by means of analytical approaches, which require several simplifying assumptions as well as TRT durations of at least fifty hours and constant heat injection. In this context, a detailed dynamic numerical model of the borehole can help reducing both the uncertainties, associated with these simplifying assumptions, and the required test duration. This paper presents a TRNSYS tool to obtain the grout and ground thermal properties by means of a parameter estimation technique in conjunction with a two-dimensional dynamic numerical model, the B2G model, which is able to provide accurate results with a much shorter testing time and without the necessity of a constant heat injection.

The methodology to estimate the borehole and ground characteristics has been validated thanks to the analysis of a set of experimental TRTs for U-pipe vertical boreholes carried out in different type of soils and borehole geometries. Results show that, for the analysed tests, it is possible to obtain an accurate and fast estimation of the ground thermal conductivity with reductions of the necessary TRT duration of up to a 70%, with a total uncertainty between ±10% and ±18%, considering not only the uncertainty introduced by the reduction of the test duration, but also the main sources of uncertainty.

Keywords: Ground source heat pump; Borehole heat exchanger; Ground properties estimation; Thermal Response Test; B2G model

Introduction

Nowadays, environmental issues as carbon emissions and global warming, but also oil dependency are a big concern that must be solved. European regulation has adopted different strategies during the last years in order to reduce the carbon emissions and other pollutants, promote the use of renewable energies and increase the energy efficiency of the systems.

Aligned with the Europe 2020 targets[1] , a transition to a reliable, sustainable and competitive energy system was launched in the last ten years. This strategy included the development and introduction to market of affordable, cost-effective and resource-efficient technology solutions to decarbonize the energy system in a sustainable way. The geothermal energy was among the proposed solutions [2].The EU energy targets for 2030 and 2050 are even more ambitious, as stated in [3] and [4], in line with the Paris Agreement objective to keep the global temperature increase well below 2°C and pursue efforts to keep it to 1.5°C.

The contribution of renewable HVAC systems to the EU energy targets by 2030 and 2050 strongly depends on the availability of reliable, efficient and affordable technology for the replacement of energy systems using fossil fuels. Concerning space heating and cooling in buildings, Ground Source Heat Pump (GSHP) systems become one of the most efficient heating and cooling renewable technologies currently available and a great alternative to conventional systems [5], [6].

However, despite being more efficient, the high investment cost of GSHP systems has been a handicap for its widespread use especially in zones like the South of Europe, in comparison with northern countries, where the use of GSHPs for heating applications is further extended.

Regarding the cost, the Ground Source Heat Exchanger (GSHE) component is one of the most expensive parts of the system. There exists a wide variety of configurations [7], [8]. Among them, closed loop systems are the most commonly used, as the environmental impact is quite lower in comparison with open loops. Among the closed loop systems, vertical GSHEs, also called Borehole Heat Exchangers (BHEs), are the predominant GSHEs used for both residential and non-residential GSHP applications [5]. In this configuration, a borehole is drilled vertically into the soil and a heat exchanger is introduced. The gap between the heat exchanger and the borehole wall is normally filled with a grouting material. The most extended BHE configuration is the single U-tube, in which two straight pipes (downward and upward), are connected by a U-turn at the bottom.

One of the main reasons why the BHE is so expensive is due to the high cost involved in manufacturing so long pipes and burying them below the ground level (sometimes more than 200 m deep). For this reason, in the design of these BHEs, the necessary length or depth should be optimized in order to obtain a good efficiency in the heat transfer with the ground, at a reasonable cost. This means that the heat exchanger, whose length is highly dependent on the thermal properties of the ground, should not be under-sized (low efficiency) nor over-sized (high cost).

In this context, it is of utmost importance to have a good estimation of the ground thermal properties for the optimal sizing of the BHEs. In order to characterize the thermal response of the ground and make an in situ estimation of its thermal properties, a geothermal thermal response test (TRT) is needed. A conventional TRT mainly consists of either injecting or extracting a constant value of thermal power into the BHE by means of heating up or cooling down (as presented in [9]) the fluid that circulates through it. Then, the dynamic evolution of the inlet and outlet temperatures in the BHE provides the experimental data considered to estimate the thermal properties of the ground and the BHE thermal resistance used by engineers in the GSHP system design process [10]. This is the common procedure used for more than two decades, ([11], [12]).The recommended durations for the test are 36-48 hours at least [13].In order to reduce the cost, it would be desirable to shorten this duration as much as possible but still being able to estimate the ground thermal properties with enough accuracy. Another issue is the necessity of having a constant heat injection during the test, requiring a heat injection equipment and control that increases the cost of the test.

Different modelling approaches can be found in literature to estimate the ground thermal properties. They can be mainly classified into two categories: analytical approaches such as the line source model [14] and cylinder source model [15], which require several simplifying assumptions and long TRT durations [13]; and numerical approaches, which imply the use of more detailed BHE dynamic models and parameter estimation procedures with iterative methods. These parameter estimation procedures consist of tuning the systems' thermal properties in order to match the experimental data with the values numerically obtained. This matching is usually carried out as an inverse heat transfer problem using a least squares minimization approach within an iterative scheme.

In [16], a critical review of the different analytical and numerical methods found in literature is presented, where the different approaches including one-, two-, and three-dimensional models, available for processing the experimental data resulting from the TRT, are discussed and compared. Regarding the parameter estimation procedures analysed, different strategies were followed depending on the number of unknown parameters considered. Several authors ([17], [18] and [19]) observed that the simultaneous estimation of both the ground and grout thermal conductivities and volumetric heat capacities over the entire duration of the TRT is problematic as they are strongly correlated by means of the diffusivity. This could lead to an infinite combination of conductivities and volumetric heat capacities that could be suitable solutions of the parameter estimation procedure.

In [17], a transient, two-dimensional, numerical finite volume model for a BHE [20] is used to evaluate the performance of a ground loop heat exchanger for parameter estimation, where the thermal conductivity of the grout and the ground are estimated for a set of experimental TRTs. It is concluded that, in order to be able to do the TRT in an amount of time shorter than 50 hours, a possible approach is to improve the model's accuracy in the first few hours. However, special attention should be paid to the computational cost when more complex and detailed models are considered.

In [21], a detailed three-dimensional numerical model is used to estimate the grout and ground thermal conductivities and volumetric heat capacities by splitting the estimation procedure into two subsequent steps in which the short-term (first 2-5 hours) and long-term (24-50 hours) TRT were considered separately, with a maximum deviation between the experimental and numerical data of 0.2 K approximately. However, it does not allow a TRT duration lower than 50 hours.

A new method to estimate the ground and grout thermal conductivities and diffusivities using the infinite composite-medium line source model was described in [22], reducing the required TRT duration to $t = 5r_b^2/\alpha_b$, where r_b represents the BHE radius and α_b, the grout thermal diffusivity. Good estimations were obtained for TRT durations longer than 28 hours in the TRT used in this paper.

Aranzabal et al. developed a 3D finite element model in COMSOL in order to estimate the depth-specific ground thermal conductivity profile using experimental data from a DTRT (Distributed Thermal Response Test) and an inverse numerical procedure [23]. For this purpose, they used the borehole temperature profile after 72 hours of heat injection. The main drawback of this approach is that the numerical simulations are time consuming, stating that a simpler model, like the B2G approach (the dynamic BHE model used in this work), could reduce the computational cost.

Another possible approach to reduce the TRT needed duration consists of using parameter estimation methods performed simultaneously during the TRT such as adaptive techniques, which could be used to tell the operator when to stop the TRT. The research work presented in [24] establishes a stopping criterion for ongoing TRTs of vertical BHEs. It was concluded that, for the experimental TRTs considered, the TRT duration needed was in the range of 17-28 hours in the cases analysed.

The minimum TRT duration required for applying the line source model is presented in [18], getting values in the interval of 5-21 hours (depending on the borehole geometry and grout and ground thermal properties). However, the method requires knowing the grout and ground thermal conductivity beforehand. This implies either the need of applying an analytical model to determine the conductivity in a conventional TRT with a minimum duration of 50 hours, or considering the values available in literature [25] for each type of ground and grout, which have a significant variation, and could lead to inaccurate calculations of the TRT minimum duration.

In [26], four new first-order approximation models using the time derivative of fluid temperature to analyse the first hours of the heating and recovery phases of a TRT were presented, opening the door to future interpretation methods that could potentially shorten the duration of a TRT down to 3 hours, especially for BHE with a low thermal resistance. However, this method implies the need of keeping a constant heating power and flow rate during the test in order to be successfully applied, which is a limitation to its widespread use in conventional TRTs commercially used.

The aforementioned methodologies require a long heat injection period (most of them more than 50 hours) and/or a constant heat injection during the test. A new methodology in which it is possible to reduce the heat injection period to a one day test (less than 16 hours) and avoid the necessity of a constant heat injection would mean a reduction in the cost and an increase in the feasibility of these tests, being able to obtain a good estimation of the ground thermal properties and then, to size properly the required borehole heat exchanger area in order to optimize the heat transfer with the ground at an affordable cost.

In this context, an innovative tool to estimate the ground thermal properties applied to a TRT, but without the necessity of a constant heat injection and much shorter heat injection periods, in comparison with conventional methods, has been developed and presented in this work. The methodology used consists of a parameter estimation technique in conjunction with a two-dimensional dynamic numerical model, the B2G model, and was implemented as a TRNSYS tool.

One important innovation introduced by the present research work relies on providing the researches and other stakeholders in the low enthalpy geothermal energy field, with the TRNSYS tool where the parameter estimation procedure is programmed in conjunction with the B2G dynamic numerical model for vertical single U and coaxial boreholes. Additionally to the TRNSYS tool, the installation files of the B2G model will be provided in the Appendixes section of this paper (both for an extended version for BHE dynamic modelling in TRNSYS for coaxial and single U BHE).

The B2G model was developed to reproduce the short-term behaviour of a BHE using a simple thermal network and only the portion of ground that was affected by the heat exchange between the BHE and the ground, which allows to reproduce the dynamic evolution of the fluid temperature with a low computational cost and a high accuracy [27]. It has been developed for a U-tube configuration and validated experimentally using different tests and BHEs in different locations [27], [28]. Furthermore, it was validated for long-term periods coupling the B2G with a g-function model [29].

The B2G model was previously used as a parameter estimation tool in [30] where a very preliminary version of the model (only one ground node that was experimentally adjusted) for single U BHEs was used to estimate the effective ground thermal conductivity using data from the first 15 hours of a standard TRT. The BHE was located at the *Universitat Politècnica de València* campus in Valencia (Spain). Using an inverse heat transfer problem approach, the model was able to reproduce the outlet temperature with a maximum deviation of 0.3

K, which occurred during the first hour of the test. The RMSE at the end of the simulation was 0.094 K, lower than 0.1 K (the common tolerance for PT100 sensors).

In [31] a new upgraded version of the B2G dynamic model was presented for a coaxial BHE, which included several new features to better reproduce not only the short-term but also the mid-term (up to 5 days) behaviour of the BHE. Particularly, the model of the surrounding ground was improved. It included a greater number of ground nodes (three in total) in the thermal network. The innovation of this new feature in the B2G model is that the ground nodes are automatically located by means of polynomial correlations for any type of ground, geometry and operating conditions. The new upgraded model was programmed in TRNSYS [32] and validated against experimental data from a dual source heat pump installation in Tribano (Padua, Italy). It proved to be capable of accurately reproducing the short-midterm (up to five days) behaviour of the BHE, with a deviation lower than 0.12K and low computational cost (2.5s for a 24 h simulation period in a modern computer).

This paper presents for the first time the upgraded version of the B2G model for single U BHEs as well as its experimental validation for the same TRT test that was formerly considered in [27]. Thanks to the better modelling of the surrounding ground, the accuracy of the model was improved without increasing the computational cost. This upgraded version of the model will be used jointly with a parameter estimation procedure in order to estimate not only the conductivity of the ground but also that of the grout.

A set of experimental TRTs will be considered for single U vertical boreholes in different type of soils and borehole geometries. Using an optimization algorithm, both the conductivity of the ground and the grout will be determined only requiring between 11 and 16 hours of TRT duration for all the TRTs considered, which means up to 70% TRT time reduction compared to other similar approaches existing in the reviewed literature. This short duration of the TRT needed, would allow the operator carrying out a TRT in only one day, with a consequent cost reduction. Additionally, an uncertainty analysis will be performed in order to evaluate the increase in the uncertainty of the estimated conductivities due to the reduction of the heat injection time (with respect to a longer TRT of 45 hours), as well as the uncertainty introduced because of the estimation of the parameters with a high impact: volumetric specific heat of the ground, borehole radius and far-field temperature.

This paper is organized as follows: First, the numerical model considered, the validation methodology and the parameter estimation procedure programmed in TRNSYS are described. Second, the different TRT experimental data are presented. Third, the results from the experimental validation are shown, as well as the results obtained from the estimation of the ground and grout conductivities. Then, an uncertainty analysis is presented. Finally, conclusions are discussed.

1

2 Methodology

2.1 Numerical model (B2G)

The B2G model is able to simulate the dynamic behaviour of a BHE by dividing vertically the BHE in several discrete parts, reproducing the vertical thermal interaction along the BHE depth and, in each vertical division, using a 2D thermal network approach to reproduce the radial heat exchange. Regarding the modelling of the fluid, the advection is considered, so the vertical temperature evolution can be calculated accordingly. In order to reduce the computational cost of the model but keeping a high accuracy, it was used a simple thermal network with only the portion of ground affected during the period with heat exchange.

The different parts of the BHE (fluid, grout and ground) are modelled with different nodes in the thermal network and the thermal interaction between them is modelled with conducive and convective thermal resistances. The thermal capacitances of each node is also introduced to reproduce its thermal inertia.

Initially, the B2G model incorporated only one node for representing the surrounding ground around the BHE, therefore, the accuracy in the reproduction of the outlet fluid temperature was not uniform along the simulation period, leading to a better reproduction of the outlet fluid temperature at the end, but a not so accurate reproduction at the very short-term. In order to reproduce with a higher accuracy both the very short-term and short-mid term evolution of the fluid temperature, three ground nodes have been considered in the thermal network instead of only one. So now it is possible to have a higher accuracy of the BHE thermal response during the different heat injection periods, without greatly incrementing the complexity of the model. Furthermore, a methodology was developed in order to calculate the optimal position of these ground nodes, depending on the BHE geometry (BHE radius), the heat injection time and the ground thermal properties (thermal conductivity and volumetric capacity). In addition, the vertical heat conduction was considered for the grout and ground nodes. The original B2G model for a single U-tube BHE is detailed in [27], where all the balance equations, parameters calculation and the numerical resolution are described for the model with only one ground node. The resolution and parameter calculation of the upgraded model is analogous to the previous one. The B2G model has also been adapted to a coaxial BHE configuration and described in [31].

The B2G model has been implemented as a TRNSYS type both for the U-tube and coaxial configuration (see Appendix A. TRNSYS types).

2.2 U-tube B2G model

The initial B2G model was created for a U-tube configuration and consisted of a 5C6R-n model (five thermal capacitances, six thermal resistances and *n* vertical divisions). It was validated using different BHEs and test conditions [27], [28] and was able to reproduce the BHE behaviour with an absolute error within 0.15K. It was also validated coupled with a g-function model, so it was possible to simulate the BHE behaviour during the operation of a GSHP system [29], considering both the short-term BHE response (B2G model) and the long-term response of the ground (g-function).

2.2.1 Upgraded thermal network

The new upgraded version of the U-tube B2G model consists of a 6C8R-*n* model. The thermal network is presented in Figure 1, where T_1 and T_2 represent the upward and downward fluid inside the pipe, T_{b1} and T_{b2} represent the grout (it is divided in two regions). The first ground node (T_{g1}) represents the closer ground region in contact with the borehole, which has a higher influence in the short-term response of the BHE. The second ground node (T_{g2}) represents the further ground region, with a lower influence in the short-term response but a higher influence in the mid-term response. The undisturbed ground node (T_{ug}) represents the far surrounding ground, which keeps a constant temperature, as it remains undisturbed during the heat injection period assumed in the model.

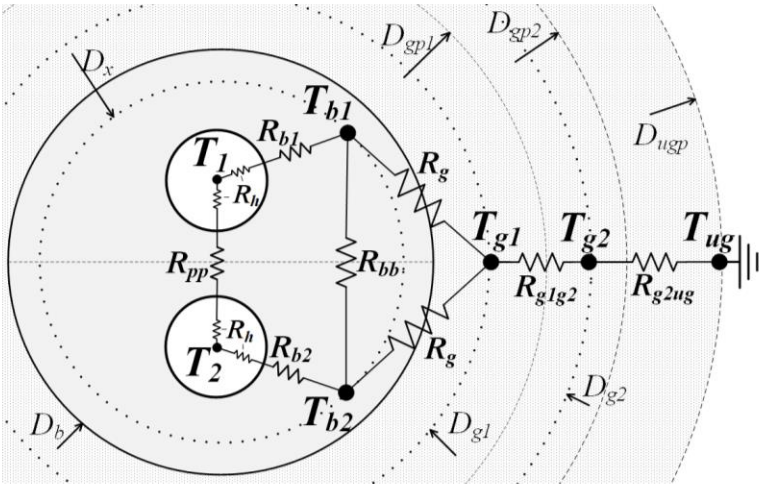


Figure 1. Thermal network of the B2G model at each vertical division for U-tube configuration

The convective and conductive heat transfer between the different nodes was calculated by the use of radial thermal resistances between nodes (R_h, R_{pp}, R_{b1}, R_{b2}, R_{bb}, R_g, R_{g1g2} and R_{g2ug} shown in Figure 1). The heat conduction between the vertically adjacent grout and ground nodes has also been considered by the use of vertical thermal resistances (R_{vb}, R_{vg1} and R_{vg2} shown in Figure 2). The vertical discretization of the BHE model is shown in Figure 2. The thermal inertia of each node is considered by thermal capacitances (fluid nodes C_f, grout nodes C_b, and ground nodes C_{g1} and C_{g2}). The undisturbed ground node capacitance is infinite, as its temperature remains constant.

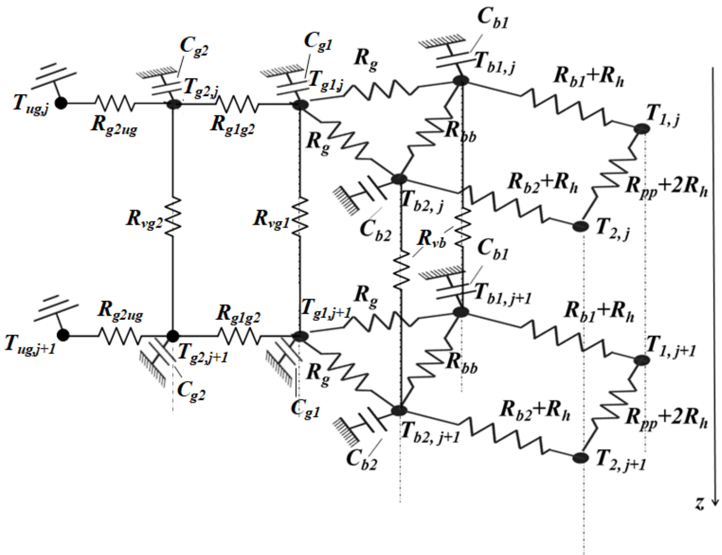


Figure 2. Thermal network of the B2G model: 3D model

2.2.2 Energy balance equations

The energy balance equations composing the system are described in the following:

- The evolution of the fluid nodes temperature results in the equations (1) and (2). The advection of the fluid is considered but the axial heat conduction is neglected (the velocity of the fluid is represented by v). It is considered the heat exchange between each fluid node and the heat exchange with the adjacent grout node. In these equations, t represents time, z represents the BHE depth direction, R_h the convective thermal resistance in the fluid nodes, R_{pp} the conductive thermal resistance between pipes and R_{b1} and R_{b2} the conductive thermal resistances between the fluid nodes T_1 and T_2 and their respective grout node (T_{b1} and T_{b2}).

$$\frac{\partial T_1(z)}{\partial t} = -v\frac{\partial T_1(z)}{\partial z} - \frac{1}{C_f}\left(\frac{T_1(z) - T_{b1}(z)}{R_{b1} + R_h} + \frac{T_1(z) - T_2(z)}{R_{pp} + 2R_h}\right) \tag{1}$$

$$\frac{\partial T_2(z)}{\partial t} = -v\frac{\partial T_2(z)}{\partial z} - \frac{1}{C_f}\left(\frac{T_2(z) - T_{b2}(z)}{R_{b2} + R_h} + \frac{T_2(z) - T_1(z)}{R_{pp} + 2R_h}\right) \tag{2}$$

- For the grout inside the borehole, two separated regions are considered, resulting in two different grout nodes with a lumped thermal capacitance, as shown in Figure 1. Both nodes are interconnected by a thermal resistance R_{bb} and to the first ground node by the resistance R_g, resulting in a delta-network limited to the internal borehole geometry. Furthermore, the heat exchange between the vertically adjacent grout nodes (at the depths immediately above and below) is also considered with the conductive thermal resistance R_{vb}, resulting in the equations (3) and (4).

$$C_{b1}\frac{\partial T_{b1}(z)}{\partial t} = \frac{T_1(z) - T_{b1}(z)}{R_{b1} + R_h} + \frac{T_{b2}(z) - T_{b1}(z)}{R_{bb}} + \frac{T_{g1}(z) - T_{b1}(z)}{R_g} + \frac{T_{b1}(z-1) - T_{b1}(z)}{R_{vb}} + \frac{T_{b1}(z+1) - T_{b1}(z)}{R_{vb}} \tag{3}$$

$$C_{b2}\frac{\partial T_{b2}(z)}{\partial t} = \frac{T_2(z) - T_{b2}(z)}{R_{b2} + R_h} + \frac{T_{b1}(z) - T_{b2}(z)}{R_{bb}} + \frac{T_{g1}(z) - T_{b2}(z)}{R_g} + \frac{T_{b2}(z-1) - T_{b2}(z)}{R_{vb}} + \frac{T_{b2}(z+1) - T_{b2}(z)}{R_{vb}} \tag{4}$$

- Regarding the first and second ground nodes, the radial heat transfer between each ground node and the adjacent nodes in the same vertical division is considered with the resistances R_g and R_{g1g2} (conductive thermal resistance between first and second ground nodes). In addition, the vertical heat conduction between vertically adjacent ground nodes is also considered with the conductive thermal resistance R_{vg2}, resulting in the equations (5) and (6).

$$C_{g1}\frac{\partial T_{g1}(z)}{\partial t} = \frac{T_{b1}(z) - T_{g1}(z)}{R_g} + \frac{T_{b2}(z) - T_{g1}(z)}{R_g} + \frac{T_{g2}(z) - T_{g1}(z)}{R_{g1g2}} + \frac{T_{g1}(z-1) - T_{g1}(z)}{R_{vg1}} + \frac{T_{g1}(z+1) - T_{g1}(z)}{R_{vg1}} \tag{5}$$

$$C_{g2}\frac{\partial T_{g2}(z)}{\partial t} = \frac{T_{g1}(z) - T_{g2}(z)}{R_{g1g2}} + \frac{T_{ug}(z) - T_{g2}(z)}{R_{g2ug}} + \frac{T_{g2}(z-1) - T_{g2}(z)}{R_{vg2}} + \frac{T_{g2}(z+1) - T_{g2}(z)}{R_{vg2}} \tag{6}$$

- Regarding the undisturbed ground node. It is assumed that its temperature does not change, keeping the undisturbed ground temperature at each depth: $T_{ug}(z,t) = T_\infty(z)$.

This system can be solved numerically, solving the system of ordinary differential equations, analogously as described in [27], for the previous U-tube B2G model (with only one ground node and without vertical heat conduction) and in [31], for the coaxial configuration model (including three ground nodes and vertical heat conduction). In this work, the Lax-Wendroff method has been used [33]. In this way, the temperatures of each node of the thermal network are calculated at a certain time (*t+1*), considering the temperature values at the previous instant (t).

The initial temperature considered is the same for all the BHE nodes except for the undisturbed ground node, whose temperature is set apart. Nevertheless, the initial BHE and undisturbed temperatures can be the same (for example, for a TRT application with a rest period).

2.2.3 Parameters calculation

The heat transfer and the temperature evolution of the different nodes is modelled using thermal resistances and thermal capacitances. They depend on the geometrical characteristics of the BHE and its thermo-physical properties (thermal conductivity and capacity). It is possible to consider a heterogeneous ground with different thermal conductivities and capacities forming several layers, although it will not be considered in this work.

In order to calculate the thermal capacitances (C) of the grout and ground nodes, the volumetric heat capacity (c) at each depth is multiplied by the corresponding volume of the node. Regarding the fluid nodes, it is calculated based on the fluid heat capacity (C_p), the fluid density (ρ), together with the volume of fluid in each vertical division. Thermal resistances are calculated as an addition of conductive and convective thermal resistances. The convective thermal resistance (equation (9)) is calculated using the Nusselt number and the conductive thermal resistances are calculated considering the thermal conductivity of the pipes, grout and ground at the corresponding depth as cylindrical or semi-cylindrical thermal resistances (equation (11)).

The calculation of the thermal capacitances and radial thermal resistances from the fluid nodes until the first ground node is described in detail in [27]. Regarding the thermal capacitances of the ground nodes, the vertical thermal resistances and the radial thermal resistances between ground nodes, they are detailed in [31]. A summary of the calculation of these thermal capacitances and radial thermal resistances can be found in Appendix C. Calculation of other parameters in the B2G model.

The grout nodes (D_x) can be placed between the borehole diameter (D_b) and an equivalent diameter (D_{eq}), which represents the pipes surface. The approach suggested in [34] has been used in order to calculate the equivalent surface and the equivalent diameter (equation (7)).

$$D_{eq} = D_{p,e}\sqrt{\frac{4W}{\pi D_{p,e}} + 1} \tag{7}$$

In this equation, $D_{p,e}$ represents the external diameter of the pipe and W the shank space between pipes.

2.2.3.1 Borehole resistance analytical calculation

The overall borehole resistance (R_{BHE}), which can be determined experimentally using the data from a TRT, is calculated internally in the B2G model. Figure 3 shows the procedure in order to calculate this resistance: a) the borehole resistance is defined as the thermal resistance between the fluid inside the pipes and the borehole wall, b) this resistance can be represented as two parallel thermal resistances, connecting each pipe with the corresponding grout zone, c) the thermal resistance can be split in a convective term (R_h) and a conduction term (R_c), d) since the grout node is placed between the pipes and the borehole wall, the conduction term takes into account not only the conduction resistance between the pipe and the grout node (R_b), but also the conduction resistance between the grout node and the borehole wall (R_x).

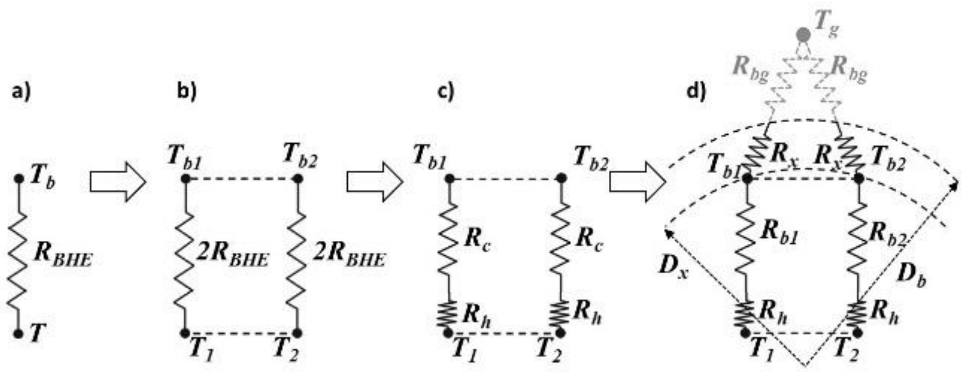


Figure 3: Borehole thermal resistance calculation: (a) borehole resistance, (b) parallel borehole resistances, (c) convective and conductive resistances, (d) final resistances configuration [27]

Hence, the borehole resistance is calculated using the equation (8).

$$2R_{BHE} = R_h + R_c \tag{8}$$

The mean convection term (R_h) is calculated using the equation (9), where h is the mean convective heat transfer coefficient inside the pipes. The Nusselt number (Nu) is calculated depending on the flow regime according to [35] and the internal pipe diameter ($D_{p,i}$).

$$R_h = \frac{1}{\pi D_{p,i} dz h} = \frac{1}{\pi dz Nu k} \tag{9}$$

In the previous equation, k represents the conductivity of the fluid and dz represents the node length in the vertical direction.

Regarding the conduction term (equation (10)), it includes the conductive heat transfer between one pipe and the grout node (R_b) and between the grout node and the borehole wall (R_x). Therefore, it is represented by the semi-cylindrical conductive thermal resistance between the pipe and the borehole wall (equation (11)). The equivalent diameter is used to represent the pipes and the heat conduction through the pipe thickness is neglected.

$$R_c = R_b + R_x \tag{10}$$

$$R_c = \frac{\ln\left(D_b / D_{eq}\right)}{\pi k_b dz} \tag{11}$$

The thermal conductivity of the grout is represented by k_b.

2.2.3.2 Ground nodes position

Regarding the position of the ground nodes, the methodology described in [31] is used. Therefore, the equations (12)-(15) are used in order to calculate the position of the first ground node (R_{gp1}), the second ground node (R_{gp2}) and the undisturbed ground node (R_{ug}), together with the coefficients shown in Table 1. In this way, the position of each ground node will depend on the borehole radius (r_b), heat injection time (t) and ground thermal diffusivity (α). Fo_b represents the Fourier number, as described in equation (15).

$$\frac{R_{gp1}}{r_b} = A_1 + B_1 \cdot Fo_b^{C_1} \quad (12)$$

$$\frac{R_{gp2}}{r_b} = A_2 + B_2 \cdot Fo_b^{C_2} \quad (13)$$

$$\frac{R_{ug}}{r_b} = A_{ug} + B_{ug} \cdot Fo_b^{C_{ug}} \quad (14)$$

$$Fo_b = \frac{\alpha \cdot t}{r_b^2} \quad (15)$$

Table 1. Calculated coefficients for the penetration radii correlations [31]

	R_{gp1}	R_{gp2}	R_{ug}
A_i	0.976794	0.926305	0.767003
B_i	0.611236	1.416714	2.312549
C_i	0.420103	0.451364	0.466674

2.3 Simulation of a TRT with the B2G model

The B2G model was implemented as a TRNSYS type, which is used to simulate a TRT during a defined injection time. The geometrical characteristics and the thermal properties of the BHE and surrounding ground are set as parameters and the measured inlet temperature (T_{in}) and mass flow rate ($\dot{m}$) are introduced as inputs in the model. Therefore, the result of the TRNSYS simulation is the outlet temperature (T_{out}), which is compared with the experimental values. The Root Mean Square Error (RMSE) between the simulated (T_{B2G}) and experimental outlet temperature ($T_{experimental}$) at the end of the simulation is calculated according to equation (16), while equation (17) is used to obtain the heat transferred to the fluid, and then to compare the experimental and simulated results.

$$RMSE = \sqrt{\frac{\sum_{t=1}^{n}\left(T_{B2G,t} - T_{experimental,t}\right)^2}{n}} \quad (16)$$

$$Q = \int \dot{m}\, C_p (T_{out} - T_{in}) dt \quad (J) \quad (17)$$

The estimation of the thermal properties of the ground and grout can be done carrying out several simulations, varying these properties and trying to minimize the RMSE at the end of the simulation.

It should be noted that the input TRT experimental data needed in the model stands for an amount of heat injection, which not necessarily must be constant during the test.

2.4 Thermal conductivities estimation procedure

2.4.1 Estimation methodology for a given test duration

In the first place, it was tried to estimate the four ground properties at the same time (ground and grout thermal conductivities and volumetric capacities), but a strong coupling between them was found and a good estimation was not possible. Furthermore, it has been reported by other authors that the estimation of the ground thermal conductivity and ground heat capacity at the same time is often problematic, so it is recommended to estimate the ground volumetric capacity based on the ground formation and calculate the thermal conductivity [17]. An uncertainty analysis is helpful in order to find the uncertainty introduced by fixing this value. Therefore, the estimation of the borehole thermal properties in this work was carried out by fixing the volumetric heat capacity of grout and ground and then, by calculating the ground and grout thermal conductivities.

In order to find the best combination of ground and grout thermal conductivities that minimize the RMSE, it is helpful to use an optimization algorithm. Thus several simulations are carried out, changing the optimization variables so that the minimum value of the RMSE is found. As the B2G model was implemented in TRNSYS, the TRNSYS tool TRNOPT was used to carry out the optimization procedure. This tool is incorporated in this software inside the TESS libraries. The TRNOPT tool is able to couple the TRNSYS simulation software with the GENOPT optimization algorithms developed by Lawrence Berkeley National Laboratory (LBNL) [36]. In this work, the Hooke-Jeeves optimization algorithm (a direct search solution for numerical and statistical problems) [37] is the one used.

The initial guesses of ground and grout conductivity are estimated from tabulated data, as in the Soil and Rock Classification for the Design of Ground-Coupled Heat Pump Systems Field Manual [38] or Ground-Source Heat Pumps: design of geothermal systems for commercial and institutional buildings [25], based on the composition of the soil in which each TRT was carried out. Regarding the volumetric heat capacities, they are estimated based on the data provided from the TRT or tabulated data. The geometry of the BHE is introduced as a parameter and the experimental data (inlet temperature and mass flow rate) are introduced as inputs. The time of heat injection for which the estimation of conductivities is carried out is introduced as an additional parameter, so that the conductivities will be estimated for that specific injection time (also called *test duration*). The methodology is schematized in Figure 4.

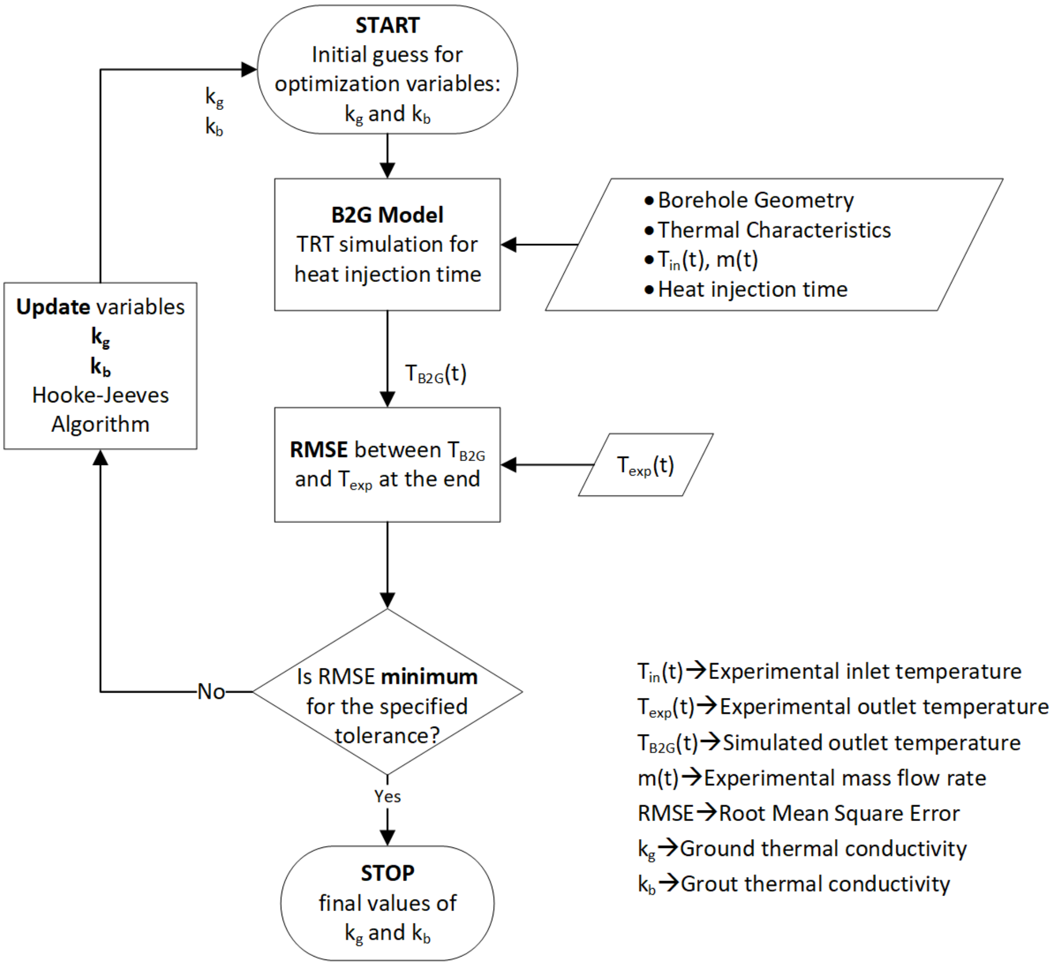


Figure 4. Flow diagram of the optimization methodology to estimate the thermal conductivities for a specific test duration (heat injection time)

It should be noted that this estimation of conductivities can be carried out for different test durations of the same TRT. The estimation obtained might vary for different test durations. Therefore, a procedure to determine the minimum time required to accurately estimate these thermal conductivities is necessary, as it will be introduced in the following. Additionally, section 4.3 presents an uncertainty analysis, where the impact of the TRT duration in the estimation of the thermal conductivities will be addressed.

2.4.2 In-situ procedure applied to a TRT and minimum TRT time

Applying the methodology explained in the previous section, the results obtained for a given test duration (t) are:

- Grout conductivity (k_b).
- Ground conductivity (k_g).
- RMSE obtained with the calculated values of k_b and k_g.

This methodology could be applied in-situ during the TRT duration, calculating the thermal conductivities and RMSE in intervals of one hour, therefore a stop criterion for the TRT duration must be defined. For this purpose, the variations of the ground conductivity (Δk_g) and RMSE ($\Delta RMSE$) with respect to the previous values are calculated (equations (18) and (19), respectively) and the TRT would be stopped when these variations are below a certain tolerance (in this work a 2% of variation per hour was used). This time will be referred in the following as *stop time*.

$$\Delta k_g(t) = \left| \frac{\left(k_g(t) - k_g(t-1)\right) / k_g(t-1)}{\Delta t} \right| \cdot 100 \quad \left(\frac{\%}{h}\right) \tag{18}$$

$$\Delta RMSE(t) = \left| \frac{\left(RMSE(t) - RMSE(t-1)\right) / RMSE(t-1)}{\Delta t} \right| \cdot 100 \quad \left(\frac{\%}{h}\right) \tag{19}$$

Where Δt is the heat injection time step (1 hour).

Therefore, when both the variations of ground conductivity and RMSE for a certain injection time are below this percentage with respect to the previous calculated value, it is considered that the TRT can be stopped and the last values of conductivities are considered the estimated representative values, as shown in Figure 5.

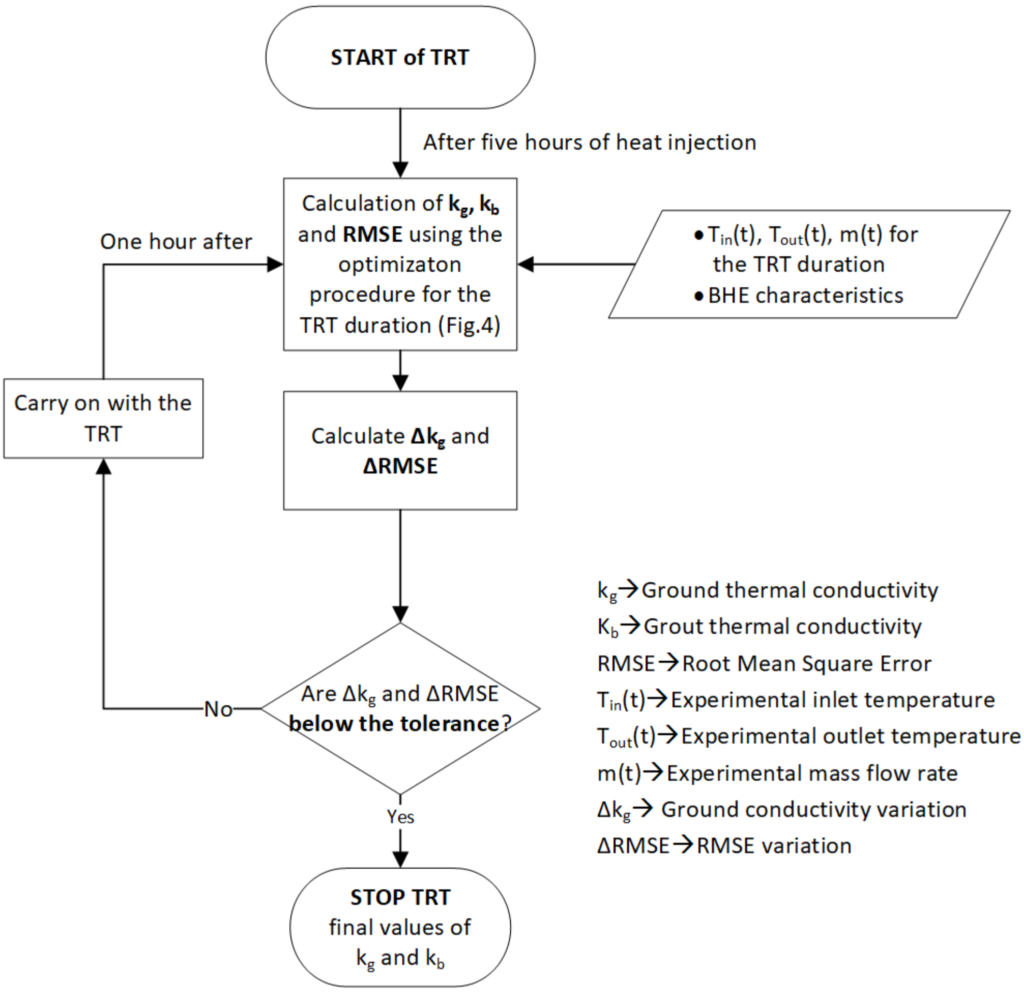


Figure 5. In-situ procedure to estimate the thermal conductivities from a TRT and stopping criterion

3 Experimental Data

Three different TRTs carried out in different locations were used for the estimation of the thermal conductivities in U-tube BHEs with different geometries, depths and soils. The ground and BHE characteristics are summarized in Table 2.

3.1.1 TRT 1: KTH water filled BHE in Sweden

The first TRT used is a DTRT was carried out in a 260 m deep water filled BHE installed in Sweden, at the KTH University, in Stockholm [27], [39], [40]. The groundwater level was 5.5 m below surface and no significant groundwater flow was found. The type of soil is rock. The U-tube pipe is made of PE 40x2.4 mm and a length of 257 m. The BHE was vertically divided in 12 sections of 20 meters each and the first section starts at 10 m depth, thus the representative depth is around 247 m. The working fluid was an aqueous solution of 12.6% weight concentration ethanol and the mass flow rate was around 0.5 l/s.

The calculations carried out from the DTRT data at the different depths estimated rock thermal conductivity values ranging between 2.6 and 3.62 W/(m·K), the average of all the sections was 3.1 W/(m·K). Regarding the borehole resistance, the values ranged between 0.054 to 0.078 m·K/W, with an average of 0.062 m·K/W. These properties were also calculated by a conventional TRT analysis, giving values of 3.08 W/(m·K) of rock thermal conductivity and 0.063 W/(m·K) of borehole resistance (if the average temperature over the whole borehole length is used instead of the average between inlet and outlet) [39].

This DTRT presents a heat injection power of around 6 kW during the first 2 hours of heat injection and after this period, the heat injected is around 9 kW.

3.1.2 TRT 2: VIA 14 BHE in Denmark

The second TRT used was carried out in one of the BHE installed at the VIA Energy Park, at VIA University College, Horsens, Denmark. The BHE used in this work corresponds to the BHE VIA 14, a U-tube BHE with a depth of 100 m. The lithology of the VIA Energy Park presented one meter of top soil, 23 m of quaternary sediments, marine sediments from the Lower Miocene until 50 m, a layer of coarse sand between 50 m and 57 m and a thick layer of silty mica clay from the Lower Miocene to 100 m. The TRT duration was 50 hours. The calculated soil thermal conductivity was 2.01±0.16 (8%) W/(m·K) and the estimated borehole resistance was around 0.11 m·K/W [24].

3.1.3 TRT 3: UPV BHE in Spain

The third TRT was carried out in a BHE located at Universitat Politècnica de València, Spain, with a depth of 40 m, a drill diameter of 160 mm and two geothermal independent pipes of 40 mm diameter and a length of 29 m and 39 m each one. The drilling filling was done with CEMEX 32.5 raff concrete and bentonite in a proportion of twelve parts of concrete and one of bentonite. The 39 m long pipe was filled with water and used as an observation BHE, while the 29 m long U-pipe was used as the working BHE.

The geological characteristics are the ones representatives of Valencia city, with gravels, sands and clays as predominant materials. Six layers were identified: a clay layer of 4 m, a peat layer from 4 m to 12 m, a gravel with small round stones layer from 27 m to 36 m and a layer of gravel with small round stones from 36 to 40m. Further information about the BHE can be found in [41], [42].

Several TRTs were carried out in this BHE, but the one used in this work correspond to a heat injection of 1 kW. According to [42], the borehole resistance extracted from this TRT was 0.12 (m·K)/W and the thermal soil conductivity 2.41 W/(m·K). However, in [41], the thermal conductivity of this BHE was estimated between 1.9 W/(m·K) and 2.8 W/(m·K), depending if the first test hours or the final ones were used to fit the data to the infinite line source model.

In this TRT, there was a sudden decrease of the heat injected in the first hours of heat injection, as it can be seen in Figure 9c).

Table 2. Characteristics of the three TRTs used for the estimation of ground and grout thermal conductivities

	TRT 1	**TRT 2**	**TRT 3**
Geometrical characteristics			
BHE representative depth (m)	247	100	29
Borehole diameter (mm)	140	160	160
External U-pipe diameter (mm)	40	40	40
Internal U-pipe diameter (mm)	35.2	32.6	32.6
Shank spacing (center-to-center) (mm)	75	100	100
Thermal properties from TRT reference			
Reference	[27], [39]	[24]	[42]
Ground thermal conductivity reference (W/(m·K))	3.1	2.01±0.16	2.41
Borehole thermal resistance ((m·K)/W))	0.062	0.11	0.12
Undisturbed ground temperature (°C)	9.1	9.63	20.2
Estimated thermal properties by tabulated data			
Ground volumetric thermal capacity (kJ/(m^3·K))	2160	2160	2600
Grout volumetric thermal capacity (kJ/(m^3·K))	4180	1500	1500
Ground thermal conductivity (W/(m·K))	3	1.8	2.3
Grout thermal conductivity (W/(m·K))	1.6	1.5	1

4 Validation of the methodology

4.1 Validation of the upgraded model

First of all, the upgraded B2G model has been validated against experimental data to prove its accuracy for calculating the outlet fluid temperature and heat injection of a TRT for different test durations. For this purpose, the same DTRT used for the validation of the previous version of the model is used [27], corresponding to the TRT 1 described in section 3.1.1.

Four simulations were carried out with different test durations (10 h, 18h, 30h and 42 h) considering around 6 hours of precirculation. The simulations were carried out in a computer with a processor Intel Core i7-7700 CPU @ 3.6 GHz 3.6 GHz and 8 GB of RAM and a simulation time step of 30 seconds. The parameter values used for the validation are shown in Table 3.

Table 3. Parameters adopted for the validation of the upgraded model

Ground thermal conductivity (W/(m·K))	3.1
Grout thermal conductivity (W/(m·K))	1.6
Ground volumetric thermal capacity (kJ/(m^3·K))	2160
Grout volumetric thermal capacity (kJ/(m^3·K))	4180
Number of nodes (-)	254

The results of the validation of the upgraded model are presented in section 5.1.

4.2 Validation of the thermal conductivities estimation and minimum TRT time

Once the upgraded B2G model was validated, the estimation of the ground and grout thermal conductivities was carried out for the three TRTs described in section 3, using the optimization procedure described in section 2.4.

For each TRT, the grout and ground volumetric heat capacities were fixed according to the data provided by the reference or tabulated data and the estimation of thermal conductivities was carried out for different test durations, from 5 hours to 24 hours in steps of 1 hour. In addition, the estimation was carried out for durations of 30 hours and 45 hours. The time step used for the simulations was 30 seconds. The number of simulations carried out in order to find the optimal values of conductivities was different for each TRT and test duration, according to the optimization procedure.

In the optimization procedure, it is necessary to fix a minimum and maximum value, as well as the initial value and step for the parameters to optimize. In all the cases, the grout thermal conductivity was varied between a value of 0.5 and 3 W/(m·K) in steps of 0.05 W/(m·K). Regarding the ground thermal conductivity, it was varied between 1 and 4 W/(m·K) in steps of 0.05 W/(m·K). The initial guesses were the ones corresponding to the tabulated data, shown in Table 2, where the volumetric thermal capacities that were used can also be found.

4.3 Uncertainty analysis

In order to consider the increase in the uncertainty of the ground thermal conductivity because of the reduction of the heat injection time, as well as other possible sources of uncertainty, it is important to carry out an uncertainty analysis, calculating the total uncertainty introduced in the methodology proposed. In this context, Pasquier and Marcotte [43] carried out a deep analysis of the uncertainty introduced in the estimation of the ground and grout thermal conductivities because of the reduction of the heat injection time using Bayesian interference methods. A simpler analysis of the uncertainty introduced by several independent sources was described by Moffat in [44] and applied by Austin et al. in [17] for estimating the ground thermal properties with shorter TRTs.

Based on the work by Austin et al. [17], similar uncertainty analyses were carried out in this work. A first analysis (section 4.3.1) was made to determine the increase in uncertainty due to the reduction of the test duration in comparison to a typical test duration (considered as 45 hours). Apart from this, a complete uncertainty analysis (section 4.3.2) was developed considering, not only the uncertainty of varying the test duration, but also the primary sources of uncertainty that showed a bigger influence according to [17].

4.3.1 Test duration analysis

In order to address the potential increase in uncertainty in the estimated parameters if the test duration is reduced from a typical test duration (here considered as 45 hours), a detailed uncertainty analysis on the estimated parameters for various test durations is performed. The uncertainty of the ground and grout thermal conductivities stated at each individual test duration is determined for each TRT considered.

The calculation of the thermal conductivities was carried out for different test durations, from 5 hours to 45 hours. Table 6 shows the results obtained for the estimation of the ground thermal conductivity and Table 7 shows those obtained for the grout thermal conductivity. It is possible to see in these tables how the uncertainty in the estimation of the thermal conductivities generally increases as the test duration of the TRT decreases.

4.3.2 Complete uncertainty analysis

This section presents the influence of the uncertainty introduced in the estimation of the ground thermal conductivity by the different parameters and inputs considered in the B2G model. The different sources of uncertainty considered for the analysis (based on the work by Austin et al. [17]), were:

- Test duration (heat injection time, without precirculation time): different times were considered until 45 hours.
- Estimated ground volumetric heat capacity: ±20%.
- Estimated borehole radius: ±10mm.
- Estimated far-field temperature: ±0.3 K.
- Mass flow rate: ±5%.
- Inlet temperature: ±0.1 K.

Being the base estimated values, for the ground and BHE parameters considered in the study, the ones shown in Table 2.

As it can be seen in Figure 7, Figure 8 and Figure 9, as well as in Table 6, not all the TRTs show the same tendency in the estimated ground thermal conductivity when varying the test duration. Therefore, for the calculation of the uncertainty corresponding to the test duration, it was decided to take the maximum and minimum values of estimated ground conductivity among all the simulated times higher than the stop time for each TRT.

The estimation of thermal conductivities was carried out following the methodology represented in Figure 4 for the stop time and varying only one parameter in each case, considering each source as independent. The percentages of variation were calculated with respect to the values obtained by the in-situ procedure (shown in Table 5 and named as *base values*).

The results of the uncertainty analysis are shown in section 5.3.2, including the uncertainty introduced by each parameter in the calculation of the ground thermal conductivity for each TRT, together with the corresponding grout conductivity and borehole resistance. In addition, the total uncertainty in the estimation of the ground thermal conductivity considering all the sources was calculated.

5 Results and discussion

5.1 Validation of the upgraded model results

The results of the validation of the upgraded model with the data from TRT 1 are shown in Figure 6, where the simulated outlet temperature is compared with the experimental one for different heat injection periods, including a precirculation period of around 6 hours. The difference between the simulated and experimental outlet temperatures is also depicted. It is possible to see that the B2G model is able to predict with a very high accuracy the behaviour of the BHE for the four periods.

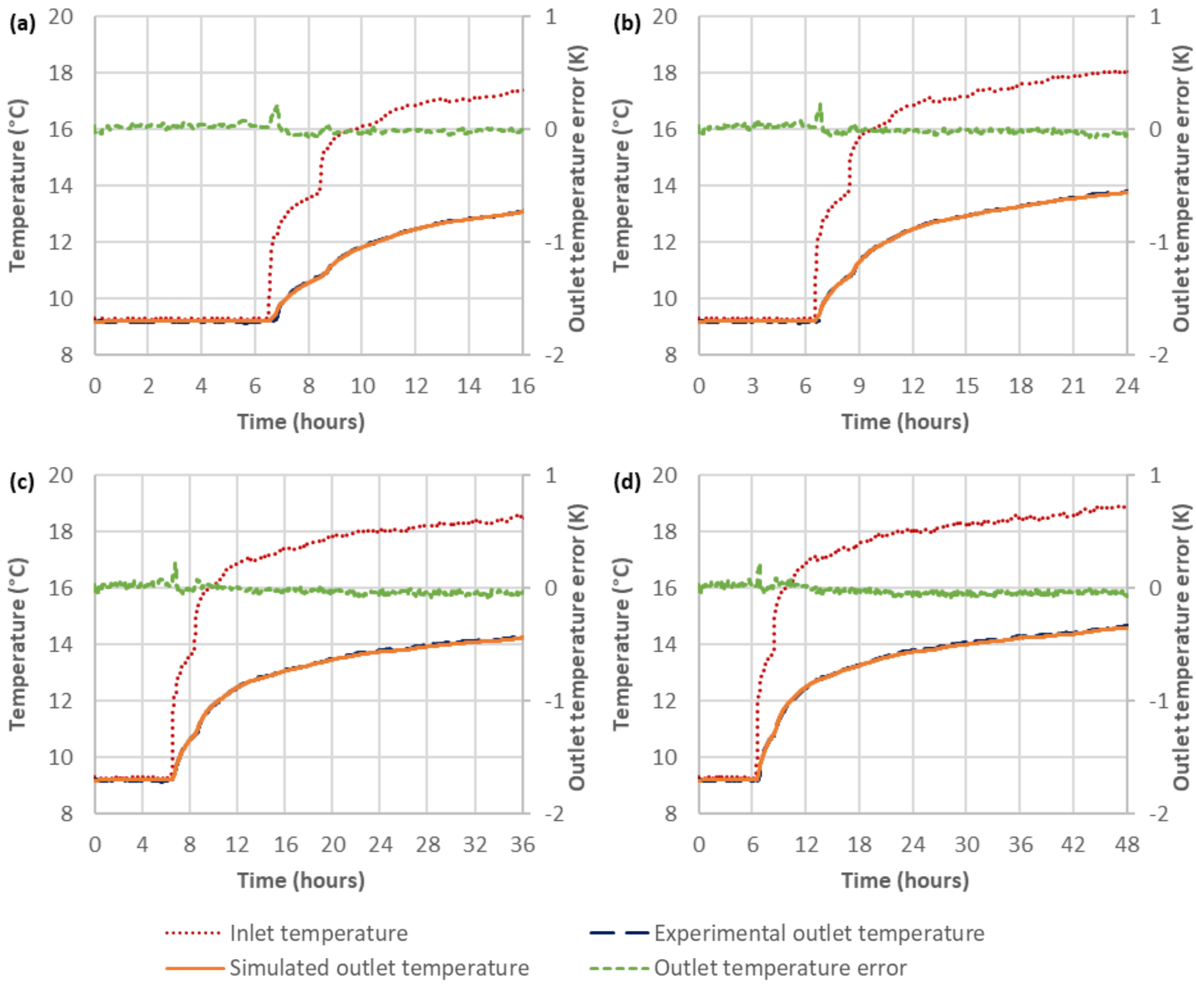


Figure 6. Model validation with TRT 1 data for different heat injection periods: (a) 10 h; (b) 18 h; (c) 30 h; (d) 42 h

The errors between the simulated and experimental results are shown in Table 4. The RMSE is calculated according to the equation (16), being below 0.05 K in the four cases. The heat transfer was calculated according to the equation (17), and the difference between the simulated and experimental results is below 0.6% in all the cases. The highest difference between the simulated and experimental is also calculated, being around 0.22K in all the cases.

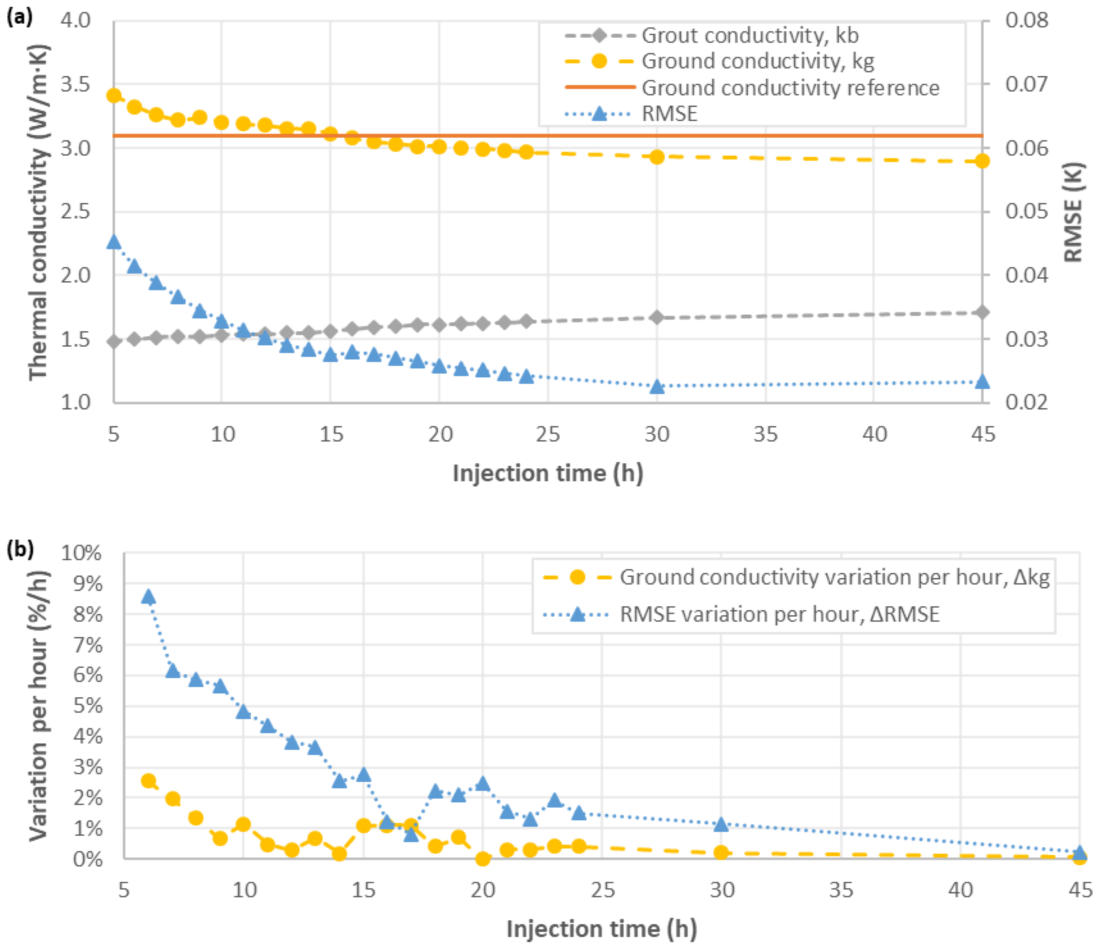
Table 4. Calculated errors for the model validation (TRT 1)

	RMSE (K)	Highest outlet temperature difference (K)	Experimental heat transfer (kJ)	Simulated heat transferred (deviation from experimental)
(a) 10 h	0.0379	0.2206	315	-0.16%
(b) 18 h	0.0336	0.2207	579	0.13%
(c) 30 h	0.0402	0.2208	968	0.46%
(d) 42 h	0.0435	0.2208	1358	0.57%

The BHE resistance was calculated following the methodology described in section 2.2.3.1, obtaining a value of 0.067 (m·K)/W for all the cases, quite similar to the obtained with the experimental data: 0.062 (m·K)/W. Regarding the simulation time of these TRT, it took around 3 seconds to simulate the longest case: a simulation of around 48 h.

5.2 Results from the thermal conductivities estimation procedure

For each TRT, the ground thermal conductivities of the ground (k_g) and grout (k_b) were calculated for each test duration by using the optimization procedure, as well as the RMSE between the experimental and simulated results. These results are shown in Figure 7(a), Figure 8(a) and Figure 9(a), for the TRT1, TRT2 and TRT3, respectively, together with the ground conductivities reported in each reference. The variations of ground conductivity (Δk_g) and RMSE ($\Delta RMSE$) for each time step in comparison with the previous value are depicted in Figure 7(b), Figure 8(b) and Figure 9(b), calculated as detailed in the equations (18) and (19). In addition, the results of the simulation of each TRT with the corresponding values of k_g and k_b for a test duration of 15 hours are shown in Figure 7(c), Figure 8(c) and Figure 9(c) and for 45 hours in Figure 7(d), Figure 8(d) and Figure 9(d).



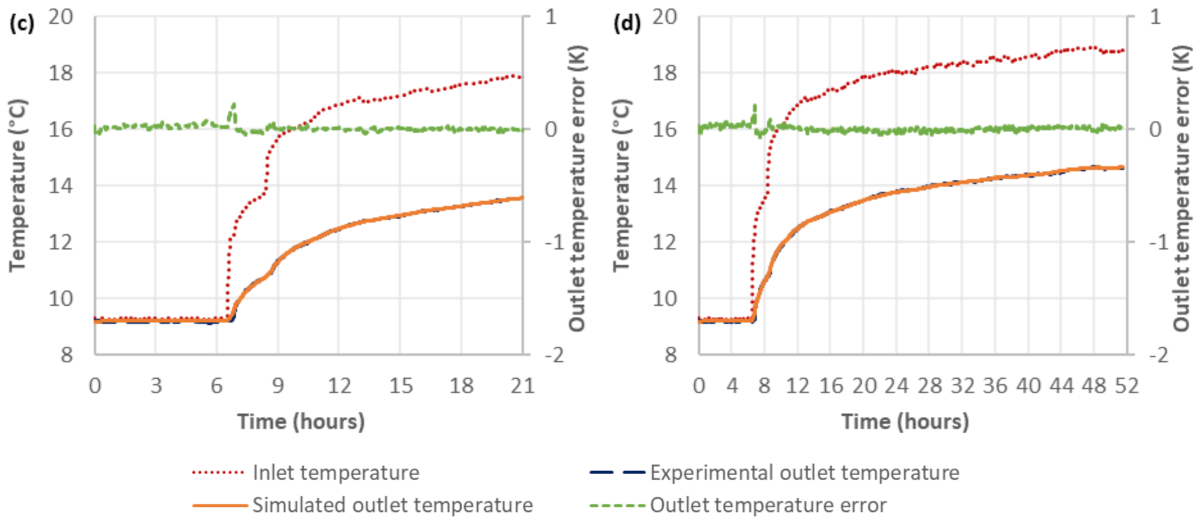
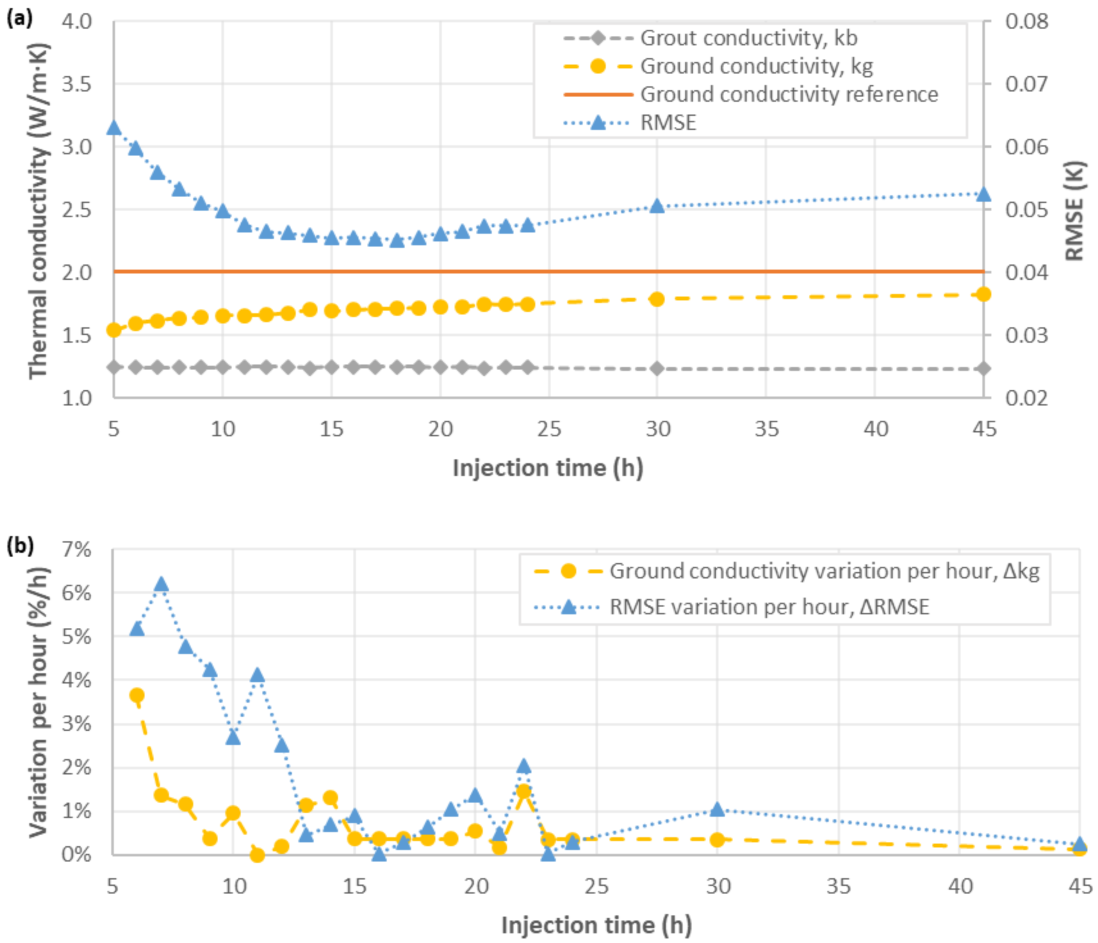


Figure 7. Thermal conductivity estimation for TRT 1 for different test durations: (a) Results and error; (b) variation of the calculated ground conductivity and RMSE; (c) TRT results for 15 hours (k_g=3.12 W/(m·K), k_b=1.57 W/(m·K)); (d) TRT results for 45 hours (k_g=2.90 W/(m·K), k_b=1.71 W/(m·K))



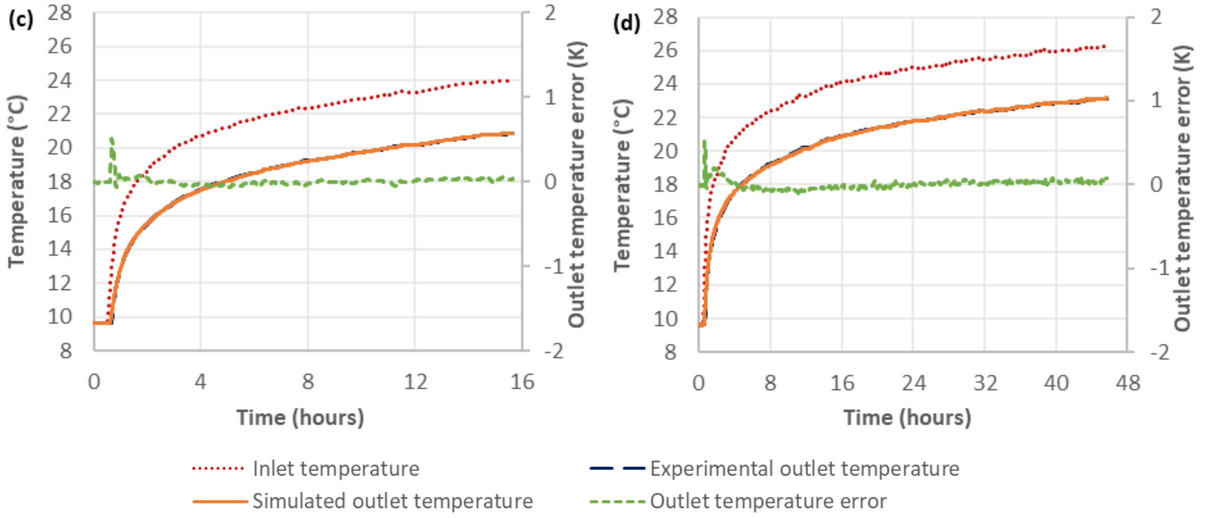
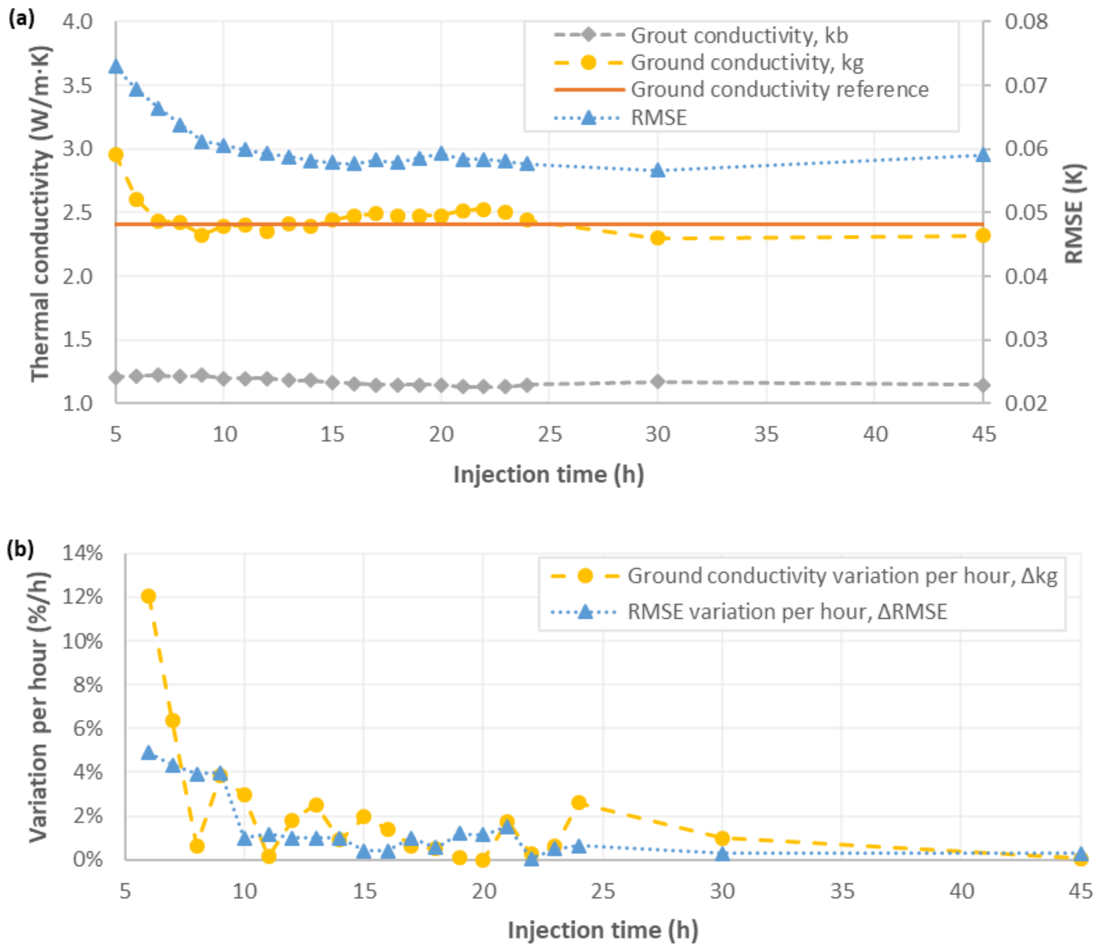


Figure 8. Thermal conductivity estimation for TRT 2 for different test durations: (a) Results and error; (b) variation of the calculated ground conductivity and RMSE; (c) TRT results for 15 hours (k_g=1.69 W/(m·K), k_b=1.25 W/(m·K)); (d) TRT results for 45 hours (k_g=1.83 W/(m·K), k_b=1.23 W/(m·K))



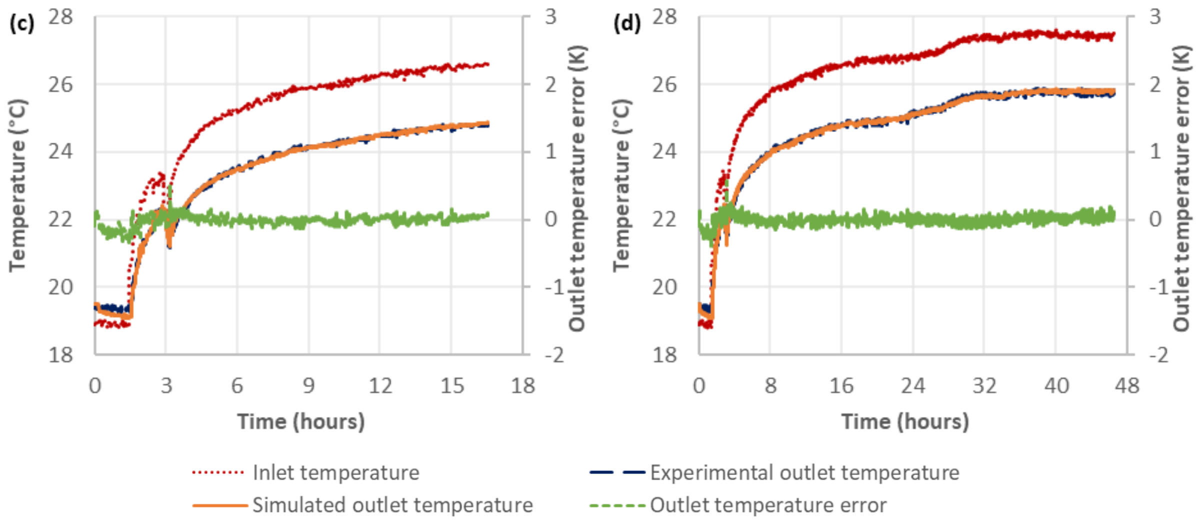


Figure 9. Thermal conductivity estimation for TRT 3 for different test durations: (a) Results and error; (b) variation of the calculated ground conductivity and RMSE; (c) TRT results for 15 hours (k_g=2.44 W/(m·K), k_b=1.17 W/(m·K)); (d) TRT results for 45 hours (k_g=2.32 W/(m·K), k_b=1.15 W/(m·K))

Applying the procedure to estimate the thermal conductivities in-situ (described in Figure 5) for each TRT, it is obtained the results shown in Table 5 (using a tolerance of 2% of variation per hour for both Δk_g and $\Delta RMSE$). The values of the resulting ground and grout conductivities are shown, as well as the borehole resistance (calculated as described in section 2.2.3.1), the stop time and the RMSE obtained from these simulations. It is also shown the computational time of carrying out the TRT simulations with the presented results, as well as the time taken by the optimization algorithm to find the solution. The iteration process followed by the optimization algorithm in each TRT is illustrated in Appendix D. Optimization algorithm iterations.

Table 5. Results of the estimation conductivities procedure

Parameter	TRT 1	TRT 2	TRT 3
Ground conductivity (W/m·K)	3.08	1.68	2.40
Grout conductivity (W/m·K)	1.58	1.25	1.20
Borehole Resistance ((K·m)/W)	0.068	0.087	0.097
Stop time (h)	16	13	11
RMSE (K)	0.028	0.046	0.060
TRT Simulation time (seconds)	2.0	1.9	1.6
Optimization algorithm time (minutes:seconds)	01:18	01:48	01:51

As it can be seen in Figure 7 and Figure 9, in TRT1 the heat injected is variable during the test and in TRT3 there is a sudden variation of heat injected during the first hours. However, the B2G model is able to accurately estimate the ground and grout thermal conductivities.

5.3 Uncertainty analysis of the parameter estimation procedure

5.3.1 Test duration analysis

The uncertainty introduced in the estimation of the ground conductivity when the test duration is reduced, from a typical value of 45 hours to different test durations, is shown in Table 6. The same results are shown for the estimation of the grout conductivity in Table 7.

Table 6. Ground thermal conductivity (k_g) estimation for different TRT durations and associated deviations in comparison with 45 hours of test duration

Duration of TRT (h)	TRT1		TRT2		TRT3	
	k_g (W/(m·K))	Deviation (%)	k_g (W/(m·K))	Deviation (%)	k_g (W/(m·K))	Deviation (%)
5	3.416	17.8%	1.538	-15.8%	2.959	27.5%
8	3.219	11.0%	1.634	-10.4%	2.422	4.3%
10	3.203	10.5%	1.656	-9.2%	2.397	3.2%
12	3.178	9.6%	1.659	-9.1%	2.356	1.5%
14	3.150	8.6%	1.700	-6.8%	2.394	3.1%
16	3.081	6.3%	1.700	-6.8%	2.475	6.6%
18	3.034	4.6%	1.713	-6.2%	2.478	6.7%
20	3.013	3.9%	1.728	-5.3%	2.475	6.6%
22	2.994	3.2%	1.750	-4.1%	2.525	8.7%
24	2.969	2.4%	1.750	-4.1%	2.444	5.2%
30	2.931	1.1%	1.788	-2.1%	2.300	-0.9%
45	2.900	0.0%	1.825	0.0%	2.322	0.0%

Table 7. Grout thermal conductivity (k_b) estimation for different TRT durations and associated deviations in comparison with 45 hours of test duration

Duration of TRT (h)	TRT1		TRT2		TRT3	
	k_b (W/(m·K))	Deviation (%)	k_b (W/(m·K))	Deviation (%)	k_b (W/(m·K))	Deviation (%)
5	1.481	-13.3%	1.250	1.5%	1.206	4.9%
8	1.525	-10.8%	1.241	0.8%	1.216	5.7%
10	1.531	-10.4%	1.244	1.0%	1.200	4.3%
12	1.541	-9.9%	1.250	1.5%	1.200	4.3%
14	1.550	-9.3%	1.238	0.5%	1.181	2.7%
16	1.578	-7.7%	1.247	1.3%	1.156	0.5%
18	1.600	-6.4%	1.247	1.3%	1.150	0.0%
20	1.613	-5.7%	1.244	1.0%	1.150	0.0%
22	1.622	-5.1%	1.238	0.5%	1.131	-1.6%
24	1.641	-4.0%	1.244	1.0%	1.150	0.0%
30	1.669	-2.4%	1.234	0.3%	1.175	2.2%
45	1.709	0.0%	1.231	0.0%	1.150	0.0%

5.3.2 Complete uncertainty analysis

A complete uncertainty analysis for the estimation of the ground thermal conductivity considering the uncertainty introduced because of these six potential sources was carried out, comparing the value of ground conductivity obtained with the one obtained in the in-situ procedure (shown in Table 5):

- The duration of the TRT. Considering the maximum and minimum value of ground conductivity (k_g) that could be obtained if a longer TRT would be considered (from the stop time until 45 hours).
- The estimated value of the ground volumetric heat capacity. The estimation of conductivities was carried out varying this value ±20% from the reference value.
- The estimated borehole radius. The estimation of conductivities was carried out varying this value ±10mm from the reference value.
- The estimated far-field temperature. The estimation of conductivities was carried out varying this value ±0.3 K from the reference value.
- The measured mass flow rate. The estimation of conductivities was carried out varying this value ±5% from the reference value.
- The measured inlet temperature. The estimation of conductivities was carried out varying this value ±0.1 K from the reference value.

The resulting ground conductivity (k_g), grout conductivity (k_b) and borehole resistance (R_{BHE}) obtained when varying these variables are shown in 8, Table 9 and Table 10, for TRT1, TRT2 and TRT3, together with the base value (shown in Table 5), the percentage of variation with respect to this base value, and the reference value shown in the corresponding references (summarized in Table 2).

Table 8. Uncertainty analysis for TRT1 and reference

Parameter	Variation	k_g (W/m·K)	k_b (W/m·K)	R_{BHE} ((K·m)/W)
Base value	-	**3.08**	**1.58**	**0.068**
TRT duration	$max.\,k_g$	3.08 (0%)	1.58 (0%)	0.068 (0%)
	$min.\,k_g$	2.9 (-5.9%)	1.71 (8.3%)	0.063 (-7.3%)
Ground volumetric capacity	**-20%**	3.23 (4.9%)	1.63 (3.2%)	0.066 (-2.9%)
	+20%	2.92 (-5.2%)	1.56 (-1.4%)	0.069 (1.3%)
Borehole radius	**-10mm**	3.06 (-0.8%)	1.39 (-11.7%)	0.059 (-13.3%)
	+10mm	3.07 (-0.3%)	1.71 (8.3%)	0.075 (11%)
Far-field temperature	**-0.3K**	2.92 (-5.3%)	1.51 (-4.2%)	0.071 (4.1%)
	+0.3K	3.27 (6.1%)	1.65 (4.6%)	0.065 (-4.2%)
Mass flow rate	**-5%**	2.96 (-3.9%)	1.44 (-8.9%)	0.074 (9.7%)
	+5%	3.2 (3.9%)	1.73 (9.5%)	0.062 (-8.6%)
Inlet temperature	**-0.1K**	3.09 (0.2%)	1.49 (-5.7%)	0.072 (5.8%)
	+0.1K	3.08 (0.1%)	1.67 (5.9%)	0.064 (-5.4%)
Reference	-	3.10	-	0.062

Table 9. Uncertainty analysis for TRT2 and reference

Parameter	Variation	k_g (W/m·K)	k_b (W/m·K)	R_{BHE} ((K·m)/W)
Base value	**-**	**1.68**	**1.25**	**0.087**
TRT duration	$max.k_g$	1.83 (8.8%)	1.23 (-1.3%)	0.089 (1.5%)
	$min.k_g$	1.68 (0%)	1.25 (0%)	0.087 (0%)
Ground volumetric capacity	**-20%**	1.82 (8.4%)	1.26 (1.3%)	0.086 (-1%)
	+20%	1.58 (-6.1%)	1.23 (-1.8%)	0.089 (2%)
Borehole radius	**-10mm**	1.73 (2.8%)	1.12 (-10.5%)	0.079 (-10%)
	+10mm	1.62 (-3.4%)	1.34 (7.8%)	0.095 (8.8%)
Far-field temperature	**-0.3K**	1.61 (-3.9%)	1.26 (1%)	0.087 (-0.7%)
	+0.3K	1.76 (5%)	1.23 (-1.8%)	0.089 (2%)
Mass flow rate	**-5%**	1.61 (-4.3%)	1.14 (-8.3%)	0.095 (9.1%)
	+5%	1.75 (4.1%)	1.35 (8.5%)	0.081 (-7.5%)
Inlet temperature	**-0.1K**	1.63 (-2.8%)	1.19 (-4.5%)	0.092 (4.9%)
	+0.1K	1.72 (2.6%)	1.3 (4.5%)	0.084 (-3.9%)
Reference	**-**	2.01±0.16	-	0.110

Table 10. Uncertainty analysis for TRT3 and reference

Parameter	Variation	k_g (W/m·K)	k_b (W/m·K)	R_{BHE} ((K·m)/W)
Base value	**-**	**2.40**	**1.20**	**0.097**
TRT duration	$max.k_g$	2.53 (5.2%)	1.13 (-5.5%)	0.102 (5.3%)
	$min.k_g$	2.3 (-4.2%)	1.18 (-1.8%)	0.099 (1.3%)
Ground volumetric capacity	**-20%**	2.59 (8.1%)	1.22 (1.8%)	0.096 (-1.6%)
	+20%	2.18 (-9.1%)	1.2 (0.3%)	0.097 (-0.2%)
Borehole radius	**-10mm**	2.39 (-0.3%)	1.05 (-12.5%)	0.09 (-7.8%)
	+10mm	2.39 (-0.4%)	1.32 (9.9%)	0.104 (6.4%)
Far-field temperature	**-0.3K**	2.17 (-9.5%)	1.2 (0.3%)	0.097 (-0.1%)
	+0.3K	2.72 (13.3%)	1.18 (-1%)	0.098 (1%)
Mass flow rate	**-5%**	2.35 (-2%)	1.1 (-7.8%)	0.106 (8.5%)
	+5%	2.49 (3.8%)	1.29 (7.6%)	0.09 (-7%)
Inlet temperature	**-0.1K**	2.47 (3%)	1.06 (-11.2%)	0.109 (11.7%)
	+0.1K	2.41 (0.4%)	1.33 (11%)	0.088 (-9.1%)
Reference	**-**	2.41	-	0.120

The total uncertainty in the estimation of the ground thermal conductivity because of the different sources is calculated and shown in Table 11. The symmetric uncertainty was calculated considering the maximum uncertainty in absolute value for each source. All the sources were considered as independent

Table 11 Uncertainty in the estimation of the ground thermal conductivity considering the primary sources

Source	TRT1	TRT2	TRT3
TRT duration (until 45 hours)	±5.9%	±8.8%	±5.2%
Estimate of the ground volumetric heat capacity (±20%)	±5.2%	±8.4%	±9.1%
Estimate of the borehole radius (±10mm)	±0.8%	±3.4%	±0.4%
Estimate of the far-field temperature (±0.3K)	±6.1%	±5%	±13.3%
Mass flow rate (±5%)	±3.9%	±4.3%	±3.8%
Inlet temperature (±0.1K)	±0.2%	±2.8%	±3%
Total estimated uncertainty	**±10.7%**	**±14.5%**	**±17.6%**

5.4 Discussion

5.4.1 Estimation procedure

The results of the simulations of the three TRTs show a very good agreement between the simulations and the experimental results, with RMSEs below 0.08 K in all the simulations and a high accuracy during all the TRT duration, as it can be seen in the simulations for a test duration of 15h in Figure 7(c), Figure 8(c) and Figure 9(c) and for 45 h in Figure 7(d), Figure 8(d) and Figure 9(d). There exists a peak difference at the first minutes of test, due to the sudden increase of temperature at the start of the heat injection, but after the first hour of heat injection, the accuracy becomes high. This makes the RMSE higher with short durations (the highest at 5 hours), while it decreases with the test duration, as it can be seen in the three TRTs (Figure 7(a), Figure 8(a) and Figure 9(a)), reaching a minimum around 15 hours in TRTs 2 and 3. This happens because with short tests, the bigger error that happens at the beginning has a bigger weight in the RMSE than with tests, where there are a bigger number of points with small error.

Regarding the RMSE minimum achieved in TRTs 2 and 3, the following increase might be explained due to the adjustment of the parameters (thermal conductivities) to the experimental results. When the number of points to adjust increases (higher injection times), the overall error of the adjustment is usually higher, due to the difficulty of adjusting the results with only two parameters.

Regarding the variation of ground conductivity and RMSE, it is also higher during the first hours of heat injection and decreases with time, this means that it would not be so accurate to estimate the conductivities with only a few hours of heat injection. In the presented cases, the necessary test duration (stop time) was 16 hours for the TRT 1, 13 hours for the TRT 2 and 11 hours for the TRT 3, values quite lower than the conventional ones applied with the ILS model (50 hours or more). This means a reduction in the duration of the TRT between 68% and 78% and the possibility of carrying out the TRT in one single day, instead of several following days, reducing the operating cost of the TRT and then, increasing its feasibility.

5.4.2 Time duration uncertainty analysis

The uncertainty in the estimation of the ground conductivity introduced by the reduction of the test duration from 45 hours to the stop time was +6.3% for TRT1 (test duration of 16 hours), -8% for TRT2 (13 hours) and +3.4% for TRT3 (11 hours). It can be seen that there is a monotonic increase in the uncertainty as the test duration is reduced for TRT1 and TRT2. However, the tendency in the uncertainty is not monotonic for TRT3. For this reason, for the calculation of the uncertainty introduced by the test duration in the complete uncertainty analysis, it was considered the maximum value of ground conductivity and the minimum value among all the test durations longer than the stop time.

Regarding the uncertainty introduced in the estimation of the grout conductivity, it was monotonic for TRT1, reaching a value of -7.7% at 16 hours. However, it was not monotonic in TRT2 and TRT3, reaching a value of 1.3% in TRT2 for 13 hours and 4.1% in TRT3 for 11 hours. The uncertainties introduced in TRT2 were quite small (all of them lower than 1.5%).

5.4.3 Complete uncertainty analysis

Considering the uncertainty introduced by considering longer injection times, the ground conductivity was initially estimated with an uncertainty around -6% in TRT 1, around +9% in TRT 2 and around ±5% in TRT 3. If a variation of ±20% in the estimated ground volumetric capacity is supposed, the ground conductivity was estimated with an uncertainty of around ±5% in TRT 1, ±8% in TRT 2 and ±9% in TRT 3. The variations in grout conductivity and borehole resistance are quite lower in general because of these sources.

Regarding the uncertainty introduced by the estimation of the borehole radius with an uncertainty of ±10 mm, it is quite low for the estimation of the ground conductivity in the three TRTs (around -1% in TRT 1, ±3% in TRT 2 and -0.4% in TRT 3). However, it has a bigger influence in the estimation of the grout conductivity and borehole resistance (up to 13% in some cases). On the other hand, the estimation of the far-field temperature introduces a low uncertainty in the estimation of the grout conductivity and borehole resistance, but a bigger uncertainty in the estimation of the ground conductivity (around ±6% in TRT 1, ±5% in TRT 2 and ±13% in TRT 3).

The mass flow rate measurement accuracy of ±5% introduced an uncertainty of around ±4% in all the TRTs for the ground conductivity estimation, and the inlet temperature measurement (accuracy of ±0.1K) introduced a small uncertainty (±0.2% in TRT1 and around ±3% in TRT2 and TRT3).

The total uncertainty in the estimation of the ground conductivity introduced by the six considered sources (assuming they are independent) is ±10.7% in TRT1, ±14.5% in TRT2 and ±17.6% in TRT3. The borehole radius and the inlet temperature are the sources that introduce the lowest uncertainty in the three TRTs and the other sources are in similar ranges of variation (around 6% or lower in TRT1, between 3% and 9% in TRT2 and between 3% and 13% in TRT3).

These uncertainties are in the same range of values than the ones reported for the ground conductivity estimation using the ILS (around ±8% [45]) and similar to the ones obtained in [17] with another in-situ procedure using a numerical finite volume BHE model: ±6.5% due to the TRT length, ±2.6% for average soils and ±6.3% for extremely dry soils due to the estimation of the ground volumetric specific heat, ±3.6% due to the borehole radius and ±4.9% due to the far-field temperature. However, there are some differences between [17] and the present work in the values adopted: a test duration of 50 hours was used for the estimation instead of 16 hours, 13 hours and 11 hours for TRT 1, TRT 2 and TRT 3, respectively; a lower variation of the volumetric heat capacity was used in that study: ±335 kJ/(m^3·K) against ±432 kJ/(m^3·K) for TRT 1 and TRT 2 and ±520 kJ/(m^3·K) for TRT 3; the borehole radius uncertainty was similar: ±12.7 mm instead of ±10 mm and they considered a bigger variation in the far-field temperature ±0.6 K instead of ±0.3 K. In other studies like [17], the heat injection rate or the power measurement is analysed in the calculation of the uncertainty, in this study, the heat rate or the power input are not inputs to the model, but instead the mass flow rate and the inlet temperature, therefore these two variables were analysed, obtaining values between ±0.2% and ±4.3% in all the TRTs.

As expected, the calculated borehole resistance increases when the grout conductivity decreases, as the calculation of this resistance only depends on the grout conductivity and the heat convection between the fluid and the grout, but not on the ground conductivity, as described in section 2.2.3.1.

Regarding the variation of the ground capacity, an increase in this value leads to a lower calculated ground conductivity and, generally, a lower grout conductivity. This is happening because an increase in the ground heat capacity (higher thermal inertia of the ground and then, smaller temperature change in the ground) is compensated with a higher conductive thermal resistance between the ground and the fluid. In the case of heat injection, the fluid inlet temperature would be higher than the ground temperature, and the outlet fluid temperature would be between the inlet and ground temperatures. If the inertia of the ground is higher, the ground temperature would remain lower, therefore, the difference between the fluid temperature and the ground temperature would increase, then the thermal resistance between the fluid and the ground should also increase, according to the equation (20), where ($\dot{q}$ is the heat transfer rate, R_{BHE} is the thermal resistance, T_f is the fluid temperature and T_g is the ground temperature). In order to obtain a higher thermal resistance, it is necessary the value of ground conductivity to be lower.

$$\dot{q} \cdot R_{BHE} = \left(T_f - T_g\right) \tag{20}$$

With respect to the variation of the far-field temperature and the calculated value of ground conductivity, according to the equation (20), if the far-field temperature (T_g) increases, the temperature difference between the fluid and the ground ($T_f - T_g$) decreases. Thus, the thermal resistance (R_{BHE}) must decrease for the same heat transfer rate ($\dot{q}$), so the ground thermal conductivity must increase, as it is shown in the results.

The variation of the borehole radius has little influence in the calculated ground conductivity. However, it has influence in the grout conductivity and borehole resistance: the increase of the borehole radius leads to an increase in the grout conductivity and borehole resistance for the three TRTs, as they are directly connected.

Regarding the variation of the mass flow rate, an increase on the value leads to an increase in the ground and grout conductivities and therefore, a decrease of the borehole resistance. This can be explained with the basic heat transfer equations: according to the equation (21), if the mass flow rate $\dot{m}$ increases and the same temperatures are kept, the heat injection increases. Therefore, according to the equation (20), the borehole resistance must decrease (as the ground and fluid temperatures do not change). A decrease in the borehole resistance leads to an increase in the ground and grout conductivity (there will also be a small change in the convective heat transfer coefficient as the flow rate increases, but it is quite smaller).

$$\dot{Q} = \dot{m} \cdot C_p \cdot (T_{in} - T_{out}) \tag{21}$$

The variation on the inlet temperature has a little impact on the ground conductivity estimation, but a bigger impact on the grout conductivity and borehole resistance. An increase in the inlet temperature leads to an increase of the grout conductivity and, thus, a decrease of the borehole resistance.

5.4.4 Comparison with reference values

Regarding the estimated values of ground conductivities in comparison with the reference (calculated with ILS models and reported in the corresponding references):

- TRT 1: the estimated ground conductivity was 3.08 W/(m·K), practically equal to the referenced value 3.1 W/(m·K), a difference lower than 1%. The estimated borehole resistance was 0.068 (K·m)/W, quite similar than the referenced value 0.062 (K·m)/W, a difference of 0.002 (K·m)/W.
- TRT 2: the estimated ground conductivity was 1.68 W/(m·K), the higher value obtained with the uncertainty analysis was 1.83 W/(m·K), while the referenced indicated a value of 2.01 W/(m·K), with a lower value of 1.85 W/(m·K). This means that the higher estimated value would be practically equal to the lower referenced value (a difference around 1%), and the difference between the base values would be around 16%. The estimated borehole resistance is around 0.09 (K·m)/W, while the referenced value was 0.11 (K·m)/W, a difference of 0.02 (K·m)/W.
- TRT 3: the estimated ground conductivity (2.4 W/(m·K)) was quite the same than the referenced value (2.41 W/(m·K)), a difference lower than 0.5%. The calculated borehole resistance was around 0.1 (K·m)/W and the referenced value was around 0.12 (K·m)/W, a difference of 0.02 (K·m)/W.

In this work, the tool TRNOPT was used in order to carry out the optimization procedure in TRNSYS and calculate the ground and grout conductivities automatically with a very low computational time (lower than 2 minutes in the three cases). If the final user would not have access to this tool, it is possible to carry out the optimization procedure “manually” by carrying out several simulations in TRNSYS, varying the values of the ground and grout conductivities, maybe with a lower accuracy, but still feasible, as the necessary simulation time for all the TRTs is extremely low (around 2 seconds for a simulation with a test duration of 16 hour and 1.6 seconds for a simulation with a duration of 11 hours).

Furthermore, the estimation of the ground and grout conductivities are carried out by adjusting their values in order to minimize the error in the outlet temperature, so it is not required a constant heat rate in order to estimate the ground conductivity, different from the conventional methods, where a constant heat rate during the TRT duration is necessary. This allows a simpler heat injection system for carrying out the TRT and the subsequent reduction of the equipment cost.

6 Conclusions

The B2G dynamic model has been upgraded in order to reproduce with a higher accuracy the short-mid term behaviour of a U-tube BHE and to automatically set the optimal position of the ground nodes. It was proven to accurately reproduce the BHE behaviour with a low computational time at different test durations.

This model is presented in this paper as a helpful tool in order to estimate the ground and grout thermal conductivities with the data from a TRT, but reducing the required test duration in comparison with conventional data reduction procedures (ILS) (observing up to a 70% reduction of the test duration needed in the analysed cases, with a total uncertainty between ±10% and ±18% in the estimation of the ground thermal conductivity, including not only the uncertainty introduced by the test duration reduction, but also the other main sources of uncertainty). In addition, it is not necessary a constant heat injection during the TRT duration, allowing a simpler heat injection system. These improvements mean a reduction in the cost of the TRT, increasing its feasibility in small and medium installations. This reduction is possible thanks to the use of an accurate dynamic BHE model, like the B2G model, together with an optimization procedure in order to find the best combination of conductivities that fit the experimental results with the highest accuracy.

The estimation methodology could be applied in-situ, analysing the TRT data in intervals of one hour, by analysing the variation in the estimated ground conductivity and the error on the outlet temperature estimated by the model. Therefore, the TRT could be stopped when the variation in these two results is sufficiently small.

In order to check the validity and accuracy of the proposed methodology, it was applied to three different TRTs with different BHE and ground characteristics. The estimated ground conductivities were practically the same than the ones calculated with conventional procedures (ILS) and longer TRTs in two of the three TRTs, with a difference lower than 1%. The difference in the other TRT was higher (16%). Furthermore, the estimated borehole resistances were in the range of values of the referenced values.

The uncertainty in the estimation of the ground conductivity introduced by the reduction of the test duration (compared with a duration of 45 hours) was increasing as the test duration decreased for TRT1 and TRT2, achieving values of +6.3% in TRT1 (16 hours) and -8% in TRT2 (13 hours). However, the uncertainty in TRT3 was not always increasing. The uncertainty for the calculated required test duration in TRT3 (11 hours) was +3.4%.

Regarding the total uncertainty in the calculation of the ground conductivity introduced by the estimation of different parameters was similar to other studies based on the ILS model or another BHE models: the estimation of the ground volumetric heat capacity inside the tabulated values according to the ground lithology (±9% uncertainty or lower), the use of a shorter TRT than the conventional required time (between ±5% and ±9% uncertainty), the estimation of the borehole radius (lower than ±3.5%), the estimation of the far-field temperature (between ±5% and ±13.3%), the measurement of the mass flow rate (around ±4%) and the measurement of the inlet temperature (±3% or lower) . The uncertainty introduced in the calculation of the ground conductivity by the estimation of the borehole radius was quite small for two of the three TRTs (lower than ±1%). Regarding the total estimated uncertainty, was also similar to other studies (between ±10% and ±18%)

Further research could be done in this analysis by considering other sources of possible uncertainties, for example the uncertainty of the estimation of the shank spacing. Furthermore, the influence of important ground water flows in the estimation of the ground conductivity could be carried out considering longer tests and different power injections to the ground.

In addition, it will be studied how to convert the entire TRNSYS tool described in this work as an executable program, so it could be employed by anyone interested in its use. For the moment, the B2G model is a free-available TRNSYS type (see Appendix A. TRNSYS types) and the TRNSYS project used to simulate a TRT in TRNSYS16 is also available (see Appendix B. TRNSYS TRT assisting tool).

7 Acknowledgements

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8 Appendix A. TRNSYS types

The B2G model TRNSYS types for a single-U configuration and a coaxial configuration can be found at the following link: http://imst-server.iie.upv.es/~ancamar4/B2G_TRNSYS16.zip. It contains the TRNSYS proformas and DLL libraries that must be included in the TRNSYS folder in order to use these types. A user manual is also included, as well as an installation guide. The types are developed for TRNSYS16.

9 Appendix B. TRNSYS TRT assisting tool

The tool described in this work developed for TRNSYS16 can be found at the following ling: http://imst-server.iie.upv.es/~ancamar4/TRT_TRNSYS_tool.zip. It contains the TRNSYS project used for the simulation of a TRT considering different values of the ground and grout conductivities and a user manual. The estimation can be done manually or by using the tool TRNOPT (if the user have access to it) programming the optimization algorithm as detailed in this work.

10 Appendix C. Calculation of other parameters in the B2G model

The calculation of the thermal capacitances and radial thermal resistances from the fluid nodes until the first ground node was described in detail in [27]. Regarding the thermal capacitances of the ground nodes, the vertical thermal resistances and the radial thermal resistances between ground nodes, they were detailed in [31]. In order to provide a complete description of the model, these calculations are described in the following, extracted from these two references, where previous versions of the model are shown. It should be noted that the thermal capacitances and resistances are evaluated for each vertical division with a vertical length of dz.

10.1 Thermal capacitances

The thermal capacitance of the fluid nodes (C_f) is calculated considering the fluid cross area (being $D_{p,i}$ the inner diameter of the pipe), the vertical division length (dz) the heat capacity of the fluid (C_p) and the fluid density (ρ), according to the equation (22):

$$C_f = \frac{\pi}{4} \cdot D_{p,i}^2 \cdot C_p \cdot \rho \cdot dz \tag{22}$$

The thermal capacitance of each grout node (C_{b1} and C_{b2}) is simplified as half the area of the grout, multiplied by the volumetric heat capacity of the grout (c_b) and the vertical division length, as expressed in the equations (23) and (24), according to the reference [27]:

$$C_{b1} = C_{b2} \approx dz \cdot \frac{S_b}{2} c_b \tag{23}$$

$$S_b = \frac{\pi}{4}\left(D_b^2 - 2D_{p,e}^2\right) \tag{24}$$

Regarding the thermal capacitances of the ground nodes (C_{g1} and C_{g2}), it is calculated as shown in [31]. It is considered the volumetric heat capacity of the ground (c_g) and the volume of ground in the vertical division. In this regard, the position of the ground nodes (the diameters D_{gp1} and D_{gp2}) is used to calculate the corresponding region of ground, according to section 2.2.3.2, where the calculation of the corresponding penetration radii R_{gp1} and R_{gp2}) is shown. The equations (25) and (26) show the ground nodes capacitances definition:

$$C_{g1} = \frac{\pi}{4}\left(D_{gp1}^2 - D_b^2\right) c_g dz \quad ; \quad C_{g2} = \frac{\pi}{4}\left(D_{gp2}^2 - D_{gp1}^2\right) c_g dz \tag{25}$$

$$D_{gp1} = 2 \cdot R_{gp1} \quad ; \quad D_{gp2} = 2 \cdot R_{gp2} \tag{26}$$

10.2 Radial thermal resistances

The calculation of the radial thermal resistances from the fluid nodes until the first ground node is extracted from [27], where a more detailed explanation can be found:

- The conductive thermal resistance between each grout node (placed at diameter D_x) and the fluid through each pipe (R_b) is calculated according to the equation (27), considering semi-cylindrical heat transfer. Analogously, the resistance between the borehole wall (placed at diameter D_b) and each grout node (R_x) is calculated according to the equation (28):

$$R_b = R_{b1} = R_{b2} = \frac{\ln\left(D_x/D_{eq}\right)}{\pi k_b dz} \tag{27}$$

$$R_x = \frac{\ln(D_b/D_x)}{\pi k_b dz} \tag{28}$$

- The conductive thermal resistance between the pipe nodes (R_{pp}) is modelled as a one-dimensional linear heat conduction between the pipe nodes, according to the equation (29):

$$R_{pp} = \frac{W - D_{p,e}}{D_{p,e} dz\, k_b} \tag{29}$$

- The thermal resistance between the two grout nodes (R_{bb}) is estimated as a one-dimensional heat transfer, as represented in the (30).

$$R_{bb} = \frac{W}{k_b\left(D_b - D_{p,e}\right)dz} \tag{30}$$

- The thermal resistance between each grout node and the first ground node is calculated as the sum of the resistance between the grout node and borehole wall (R_x) and the resistance between the borehole wall and the first ground node (R_{bg}), as shown in the equations (31) and (32).

$$R_{bg} = \frac{1}{\pi\, k_g\, dz} \ln\left(\frac{D_{g1}}{D_b}\right) \tag{31}$$

$$R_g = R_x + R_{bg} \tag{32}$$

The calculation of the radial thermal resistances between the ground nodes and the vertical thermal resistances is extracted from [31], where a more detailed explanation can be found:

- The radial thermal resistance between the first and second ground nodes (R_{g1g2}) and between the second and the undisturbed ground nodes (R_{g2ug}) are calculated as shown in the equations (33) and (34), where D_{ug} represents the undisturbed ground node diameter and D_{g1} and D_{g2} are calculated as the average diameter of the zone, according to the equation (35):

$$R_{g1g2} = \frac{\ln\left(D_{g2}/D_{g1}\right)}{2\,\pi\, k_g\, dz} \tag{33}$$

$$R_{g2ug} = \frac{\ln\left(D_{ug}/D_{g2}\right)}{2\,\pi\, k_g\, dz} \tag{34}$$

$$D_{g1} = \frac{D_{gp1} + D_b}{2} \;\; ; \; D_{g2} = \frac{D_{gp2} + D_{gp1}}{2} \quad (35)$$

- The vertical thermal resistance between the vertically adjacent grout nodes (R_{vb}) is calculated according to the equation (36), considering the grout surface, the vertical node length (dz) and the grout thermal conductivity (k_b):

$$R_{vb} = \frac{dz}{\frac{\pi}{4} \cdot \left(D_b^2 - 2 \cdot D_{p,e}^2\right) \cdot k_b} \quad (36)$$

- Analogously, the vertical thermal resistances between the vertically adjacent ground nodes (R_{vg1} and R_{vg2}) are calculated according to the equation (37):

$$R_{vg1} = \frac{dz}{\frac{\pi}{4} \cdot \left(D_{gp1}^2 - D_b^2\right) \cdot k_g} \quad ; \quad R_{vg2} = \frac{dz}{\frac{\pi}{4} \cdot \left(D_{gp2}^2 - D_{gp1}^2\right) \cdot k_g} \quad (37)$$

11 Appendix D. Optimization algorithm iterations

In order to illustrate the iteration process carried out by the software Genopt, using the optimization algorithm to calculate the combination of ground conductivity (k_g) and grout conductivity (k_b) that minimizes the Root Mean Square Error (RMSE) for a defined test duration (as described in section *2.4.1.*Estimation methodology for a given test duration), the values of each parameter during the process are shown for the test duration resulted from the stopping criterion.

Figure 10 shows the values of ground and grout conductivity at each iteration carried out by the optimization algorithm, as well as the value of the RMSE for this combination of conductivities, for the TRT1 and the test duration shown in Table 5 (16 hours). Analogously, Figure 11 shows the corresponding values for TRT2 and a duration of 13 hours and Figure 12 shows the corresponding values for TRT3 and 11 hours.

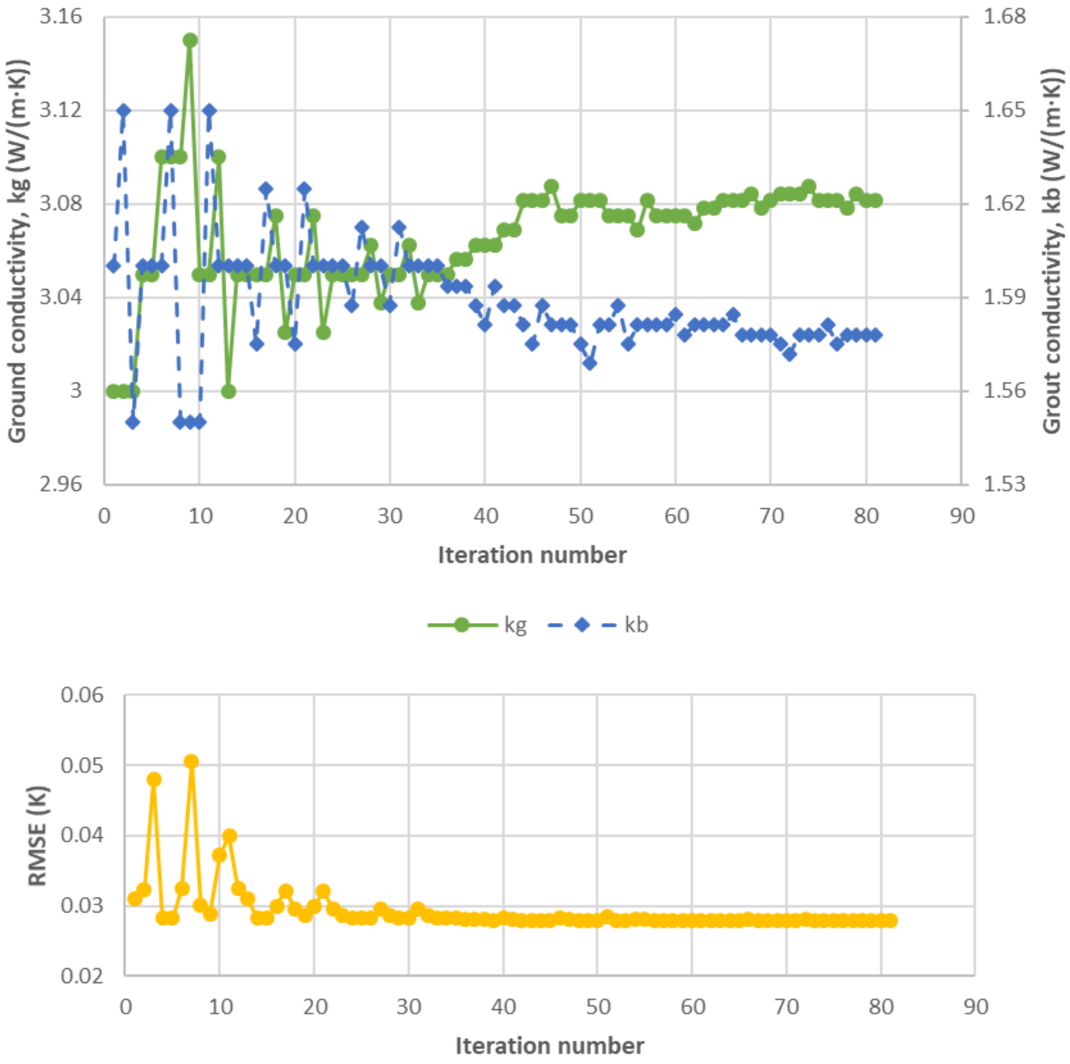

Figure 10. Genopt iterations for TRT1 and a duration of 16h (corresponding to results in Table 5)

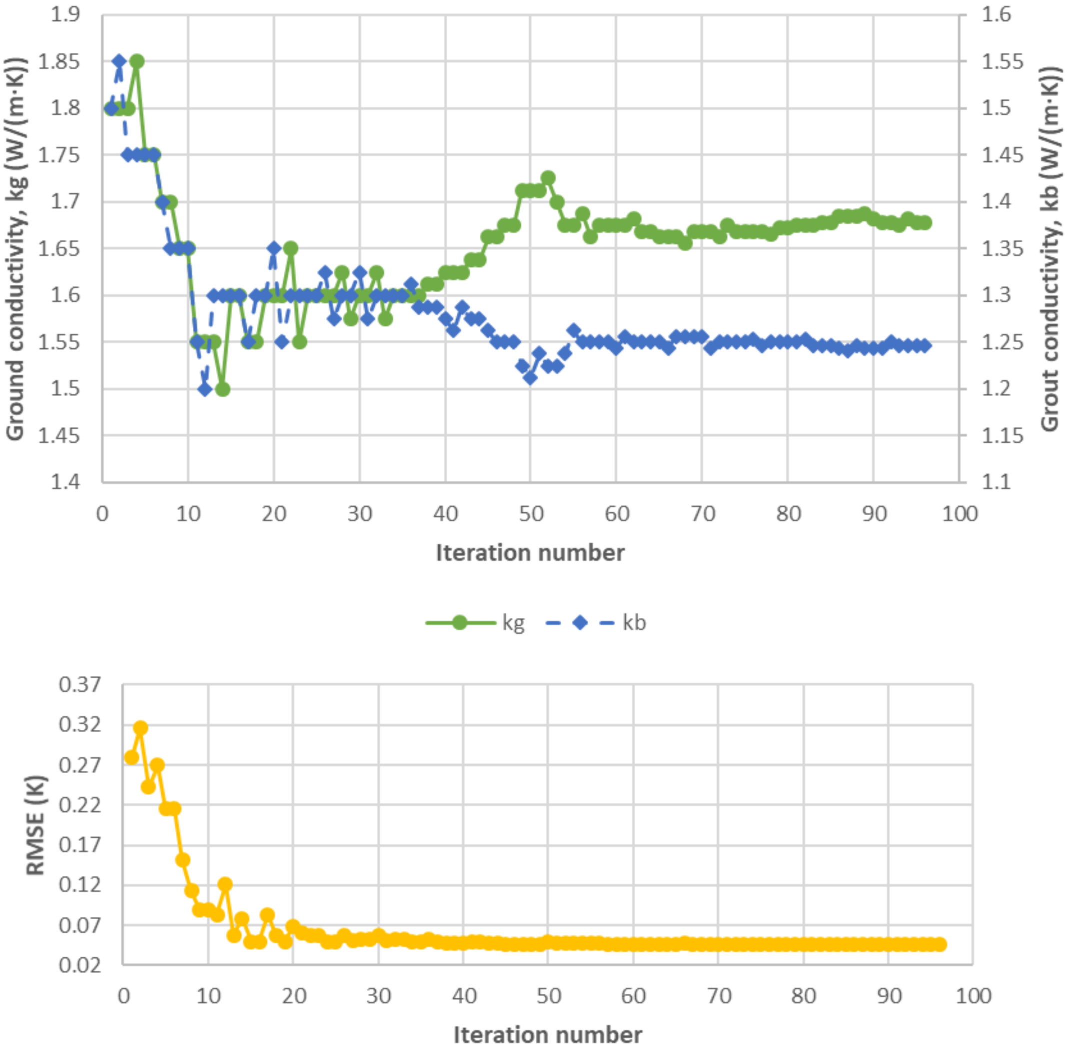

Figure 11. Genopt iterations for TRT2 and a duration of 13h (corresponding to results in Table 5)

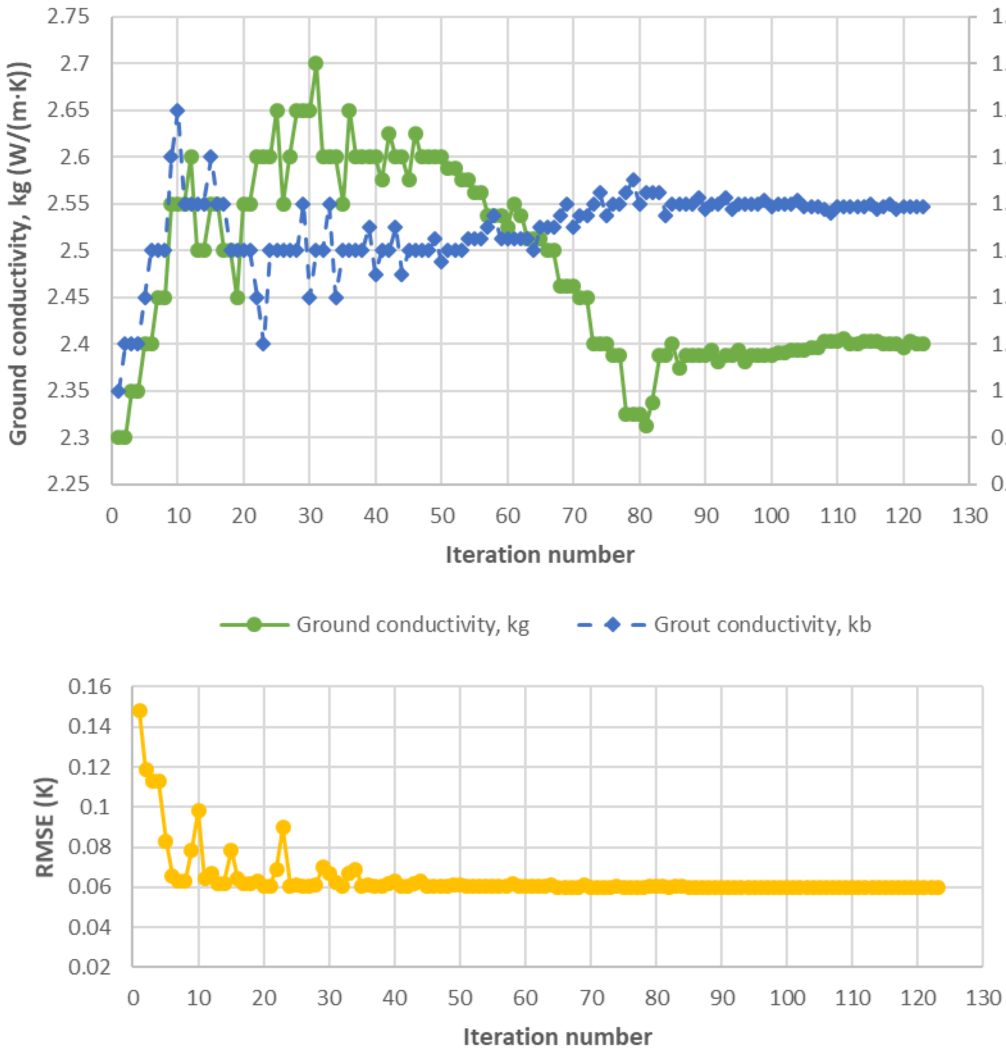

Figure 12. Genopt iterations for TRT3 and a duration of 11h (corresponding to results in Table 5)

12 References

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