Numerical evaluation of the Ground Response to a Thermal Response Test experiment

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ABSTRACT

A prerequisite for the correct design of vertical ground heat exchangers (or Borehole Heat Exchangers, BHE) for heat pump applications is the knowledge of the ground thermal properties, in particular the thermal conductivity.

The Thermal Response Test is a well known experimental procedure that allows the ground thermal and the BHE thermal resistance to be evaluated. A TRT is performed by providing a known and constant thermal power to a fluid (usually water) that circulates through a BHE buried in the site of interest; the water temperature measurements, which varies over time, represent the data to be analyzed in order to solve an inverse conduction problem. The standard analysis method addressed to parameter estimation is based on the Infinite Line Source (ILS) model.

In the present paper different 3D numerical models, are developed in order to numerically describe a TRT experiment. The calculation environment is Comsol Multiphysics® and either the thermal conduction inside the ground and grout or the fluid to pipes interactions are taken into account. The results of the simulations have been employed for a back evaluation of the ground thermal conductivity according to the standard ILS approach, to infer useful information on the errors in parameter calculation and to check the estimation capabilities of a new method based on temporal superposition and optimum search. The proposed method is in particular able to cope with situations where the TRT experiments are related to highly variable heat transfer rates to the carrier fluid. The present results show that the proposed approach is very reliable alternative to the standard ILS approach and that BHE parameters can be estimated within few percent error with respect to reference values.

1. INTRODUCTION

Ground coupled heat pump (GCHP) systems represent a valuable solution for building heating and cooling purposes. Since seasonal coefficient of performance related to GCHP can reach values up to 4, and even more, these systems can considerably reduce energy consumptions with respect to traditional fuel burning systems or air coupled air conditioning units.

GCHP systems combine a heat pump with a group of vertical or horizontal ground heat exchanger. Vertical Borehole heat Exchangers (BHE) are the most frequently adopted solution for ground coupled heat pump applications. The installation of a BHE consist in drilling a well in which a single, double or coaxial polyethylene pipes are buried till a typical depth ranging from 80 to 150 meters. The space between the pipes and the borehole wall is usually filled with heat transfer enhancing grout material. Due to the relatively high installation cost the correct overall BHE length is crucial for an optimal GCHP design. The number of BHEs and the overall BHE length needed to fulfil the building heat demand depends on the ground thermal properties of the ground, in particular, on thermal conductivity.

Thermal conductivity of the ground can be estimated though a Thermal Response Test in a pilot BHE. The TRT yields the effective (average) thermal conductivity due to the integration of the ground thermal properties along the entire depth of the BHE. This measurement procedure was first proposed by Mogensen (1983) and it is based on the Infinite Line Source model (ILS, Ingersoll 1954). The ILS model main assumptions are to consider pure conduction, constant heat transfer rate in time and space and uniform ground properties. Under those hypothesis ILS is able to describe the thermal response of an infinite ground medium. The first mobile measurement devices were introduced in Sweden (Gehlin, 1996) and in the USA (Austin, 1998) and the method rapidly across to several countries (Gehlin, 2002). This experimental method is based on constantly heating (or cooling) a fluid circulated through a BHE ready to operate: measurements of inlet and outlet fluid temperature versus time allow the estimation of the average thermal conductivity of the ground to be estimated together with the effective borehole resistance. Unfortunately the TRT model main assumptions are often not satisfied in real tests. Field test generally lack independent measurements of other soil properties different from conductivity and in addition grout thermal characteristics are often unknown, except its conductivity (Beier et al 2011). These inconsistencies are source of errors in TRT parameter estimation, as outlined in a number of recent papers (Signorelli et al., 2007, Bauer et al. 2011, Beier et al. 2011). For the above reasons, reference data sets are essential for testing TRT models and infer information on uncertainty related to TRT data analysis according to the ILS model (Fossa and Rolando, 2012).

In this paper a numerical TRT model is presented and its validation against reference data is performed. The benchmark set is constituted by laboratory measurements (Beier at al 2011), from field test and numerical simulations (Signorelli et al 2007, Bauer et al. 2011).

The calculation environment is Comsol Multiphysics and the model that was built either account for 3D transient conduction in soil and grout or the 1D (along the pipe axial coordinate) energy transient equation, including the thermal effects related to countercurrent fluids.

A possible approach to deal with situations during which constant heat transfer rates are not supplied is here presented as a case study. The proposed method is based again on the ILS solution but a optimum search is applied to the parameter estimation thanks to a superposition technique able to take into account even remarkable variations of the heat transferred to fluid during the experiments.

2. TRT THEORY AND SENSITIVITY ANALYSIS

2.1 Theoretical background

The thermal interaction between the ground and a vertical heat exchanger, when underground water circulation can be neglected, is governed by the three dimensional time-dependent conduction equation. Due to its complexity this equation is often solved numerically under a number of main assumptions: (1) constant heat transfer rate; (2) pure radial conduction in infinite medium with a uniform initial temperature; (3) constant, homogeneous and isotropic ground thermophysical properties; (4) ground water flow is neglected. Accordingly a number of one-dimensional (radial direction) and two-dimensional (radial and axial directions) analytical solutions have been proposed, able to simulate the ground response to a single constant heat pulse (Carslaw and Jaeger 1947, Ingersoll 1948, Mogensen 1983).

Thermal Response Test consists in injecting or extracting heat into a fluid (typically water) circulating inside a BHE and to record the fluid temperature evolution in time (Figure 1).

The test is usually 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 intlet, outlet and mean temperatures (T_{in},T_{out},T_{fm}), 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:

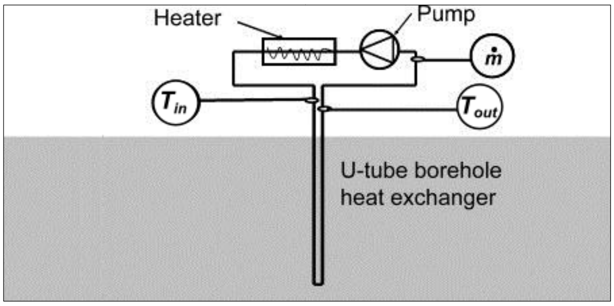

Figure 1: Thermal Response Test setup.

$$\dot{Q}' = \frac{\dot{m}c(T_{in} - T_{out})}{H} \quad [1]$$

where c is the fluid specific heat and H is the borehole length (BHE depth).

The analysis of the TRT data is usually based on the ILS model which implement the Kelvin's theory: the BHE (whose radius is r_b) is modelled as a infinitely long linear source delivering a constant thermal power per unit length.

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

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

where E_1 is the so called exponential integral which can be approximated through Eq.[3]

$$E_1(X) = -\gamma - \ln(X) - \sum_{n=1}^{\infty}(-1)^n \frac{X^2}{n \cdot n!} \cong \ln(X) - \gamma \quad [3]$$

In the present problem, X is proportional to the inverse of the Fourier number as $1/4Fo_r$ while γ is the Euler constant.

Of practical interest is the evaluation of the ground temperature at the BHE wall, say for $r=r_b$

Hence the temperature at borehole wall can be calculated as:

$$T(r_b,t) = \frac{\dot{Q}'}{4\pi k}\left(ln\left(\frac{4\alpha t}{r^2}\right) - \gamma\right) + T_{gr,\infty} \quad [4]$$

The thermal characteristics of a BHE are determined by its effective thermal resistance R_b which is defined in terms of the temperature difference of the fluid (T_{fm}) and the borehole wall (T_b) as:

$$R_b = \frac{T_{fm} - T_b}{\dot{Q}'} \quad [5]$$

The effective borehole thermal resistance accounts for the geometrical parameters of the borehole heat exchanger (pipe spacing, diameter, number of pipes, depth) and for the physical parameters (thermal conductivity of the materials, flow rate in pipes, fluid properties). The lower is the borehole resistance the higher is the quality of the BHE itself (Pahud and Matthey, 2001).

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

$$T_f(t) = \frac{\dot{Q}'}{4\pi k}\left(ln\left(\frac{4\alpha t}{r^2}\right) - \gamma\right) + \dot{Q}' \cdot R_b + T_{gr,\infty} \quad [6]$$

In this model T_f corresponds to the average between the inlet and outlet fluid temperatures.
If $\dot{Q}$ is constant, the Eq.[6] becomes a simple linear expression with respect to the logarithm of time:

$$T_f(t) = S \cdot \ln(t) + I \quad [7]$$

where the slope S and intercept I are quantities related to ground thermal conductivity (k) and to R_b respectively.
As suggested by Eq.[7] an estimation of the slope slope S and intercept I is possible through a (log)linear regression.

A typical postprocessing problem is to select the right data interval where to apply the regression analysis. Virtually any interval in the "late period" (say when some proper Fo_{rb} is elapsed) is suitable to this aim. In practical cases (and even in theoretical ones, see Beier and Smith 2003), this time window is difficult to define, for example because the heat transfer rate was fluctuating during the measurements or because the thermal properties of ground and grout are too different for ILS model successful application.

The above effects can yield to a non unambiguous evaluation of the slope S (and hence of k), which in turn results dependent on the time interval selected for its evaluation. In the next paragraphs examples of S and k evaluation according to different periods (starting from the ending condition, when the heat transfer to fluid is stopped) are presented.

The ground thermal conductivity and effective borehole thermal resistance can hence be evaluated according to the expressions [8] and [9]:

$$k = \frac{\dot{Q}'}{4\pi S} \quad [8]$$

$$R_b(t) = \frac{T_{fm} - T_{gr,\infty}}{\dot{Q}'} - \frac{1}{4\pi k}\left(ln\left(\frac{4\alpha t}{r^2}\right) - \gamma\right) \quad [9]$$

$$R_b = \frac{1}{\dot{Q}'}\left(I - T_{gr,\infty} - \frac{\dot{Q}'}{4\pi k}\left(ln\left(\frac{4\alpha}{r^2}\right) - \gamma\right)\right) \quad [10]$$

Worth noticing, Equations [9] and [10] state that there are two (almost) equivalent ways for evaluating R_b: an instantaneous value $R_b(t)$ according to Eq. [9], and an average one (Eq. [10]) which is based on a regression analysis, applied to a given time interval.

2.2 Sensitivity analysis

The hypothesis of constant transfer rate supplied to the circulating fluid is one of the essential assumption of the ILS-R_b model. Quite often this condition does not occur during standard heating or cooling thermal response test applications. In a recent paper by the present Authors (Fossa and Rolando 2012) a sensitivity analysis applied to the TRT inverse problem has been performed. According to realistic uncertainties on independent parameters, the overall uncertainty on estimated parameters has been calculated. As can be observed in Figure 2 it is the heat power variation and the undisturbed ground temperature that mostly affect the uncertainty of borehole resistance. Another meaningful effect is the one related to the uncertainty on volumetric heat capacity of the ground. Finally it must be outlined the effect of the uncertainty related to the estimation of k: this last one is in turn again severely affected by the uncertainty on the heating power, which hence plays a multiple role in affecting the results of the measurements.

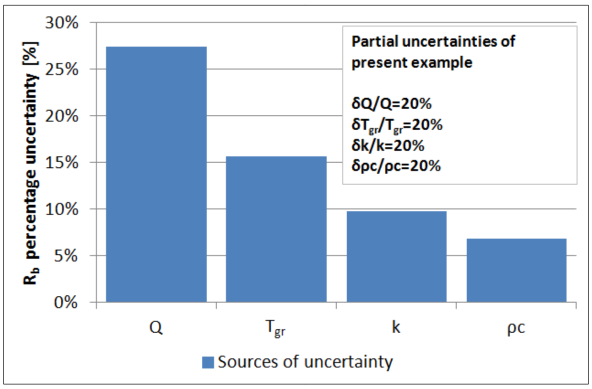

Figure 2: Sensitivity analysis related to borehole resistance uncertainty estimation.

3. NUMERICAL MODEL AND VALIDATION

Thermal Response Test represent a suitable methodology to estimate effective ground conductivity, which represents a key parameter in BHE field design.

The ILS-R_b model is characterized by assumptions whose effects in field data analysis should be assessed. Also more complex models, like the 3D one described here need to be verified and validated against reliable measurements. Unfortunately field tests generally lack of independent measurements of soil properties different from conductivity. The conductivity itself is in turn unknown by definition. Also the position of the pipes in the borehole is difficult to know in real installations (Beier et al. 2011). This is the reason why complex 3D TRT models can typically be compared with one another. The 3D conduction model presented in this investigation is based on the numerical solution of the Fourier equation in Comsol Multiphysics environment. The model is able to account for the transient behavior of ground, grout and circulating fluid. Validation against literature data is discussed and results related to a variety of test cases are presented.

3.1 Modelling the borehole and the ground

A schematic of BHE considered in the present analysis and modeled in Comsol Multiphysics is shown in Figure 3. Basically it consists of a single or double-U pipe immersed in a grout medium which fills the remaining volume between the pipes and the borehole wall. No contact thermal resistance is considered between different materials. The model domain is limited either in radial and axial direction by adiabatic surfaces. A proper portion of ground under the bottom part of the pipes is also considered to take into account the heat transfer under the BHE. The main geometrical parameters, material properties and working conditions adopted in the base numerical model are available in Table 2. Geometry and properties have been changed accordingly to perform the comparisons with different literature data.

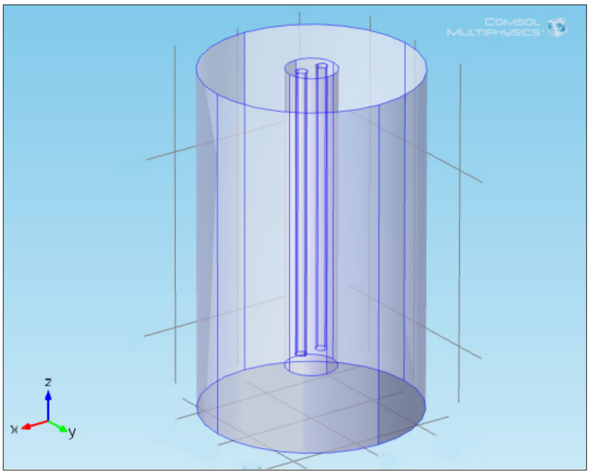

Figure 3: Comsol Multiphysics modeling of single U borehole heat exchanger. Scaling is applied.

The heat transfer process related to a TRT experiment involves mainly the unsteady three dimensional thermal conduction between the pipe walls and the ground and the convective heat transfer due to the flow of the carrier fluid into the pipes. Transient heat transfer conduction is governed by the Fourier conduction equation which under the hypothesis of homogeneous medium can be written as:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho\, c_p} \nabla^2 \mathrm{T} \qquad [11]$$

The numerical solution has been calculated with the following initial condition applied to the entire domain:

$$T(r, z, t = 0) = \mathrm{T}_{\mathrm{gr},\infty} \qquad [12]$$

The energy conservation equation (in the streamwise direction z) related to the heat carrier fluid is written in terms of *weak form boundary condition* available in Comsol Multiphysics, as done in recent papers by Corradi et al. (2008), Zanchini et al. (2010). The coupling between the inner pipe wall and the fluid is hence described as:

$$A \rho_f c_f \frac{\partial T_f}{\partial \tau} = \pm \dot{V} \rho_f c_f \frac{\partial T_f}{\partial z} + hp(T_p - T_f) \qquad [13]$$

Where h is the convective heat transfer coefficient, T_f is the local fluid temperature, $\dot{V}$ is the volumetric flow rate, T_p is the pipe inner wall temperature, r is the pipe inner radius, ρ_f is the fluid density, c_f is the fluid specific heat and p is finally the inner pipe perimeter. Depending on the stream direction (downwards or upwards) a different sign applies, as in the second member of Eq.[13].

Modelling and simulation of BHEs is complex and computationally complex mainly because of the geometrical slenderness. Since the heat exchanger has a length of 100m and a radius of 0.05m, a rescaling of the vertical coordinate z is here adopted, to obtain a more compact computational domain (Zanchini et al. 2010). Thus, a rescaled vertical coordinate $\tilde{z}$ and a thermal conductivity matrix $\widehat{K}$ have been introduced, as follows:

$$\tilde{z} = \frac{z}{a}, \widehat{K} = \begin{bmatrix} k & 0 & 0 \\ 0 & k & 0 \\ 0 & 0 & \tilde{k} \end{bmatrix}, \tilde{k} = \frac{k}{a} \qquad [14]$$

where a is a dimensionless scale factor which was selected equal to 10. Eq.[13] has been implemented in Comsol by rescaling the variables present in Eq.[14]

Table 1: Finite element model geometrical parameters, material properties and working conditions.

Parameter	Value	Units
Inner pipe radius	0.013	m
Outer pipe radius	0.016	m
Borehole radius	0.05	m
Pipes spacing	0.02	m
Ground domain radius r_b	3	m
Ground domain depth	110	m
Borehole depth (H)	100	m
Scale factor	10	
Fluid specific heat	4200	J/kg K
Fluid density	1000	kg/m^3
Fluid thermal conductivity	0.6	W/m K
Pipe specific heat	1900	J/kg K
Pipe density	900	kg/m^3
Pipe thermal conductivity	0.3	W/m K
Grout specific heat	1600	J/kg K
Grout density	1000	kg/m^3
Grout thermal conductivity	1.5	W/m K
Ground specific heat	800	J/kgK
Ground density	2500	kg/m^3
Ground thermal conductivity	2	W/m K
Convection heat transfer coefficient	1500	W/m^2K
Undisturbed ground temperature	287	K
Volumetric fluid flow	$4{\cdot}10^{-4}$	m^3/s
Total heat rate	5040	W

An extensive sensitivity analysis applied to mesh characteristics has been performed to find the best domain discretization with respect to the fluid expected temperature evolution and in terms of stabilization of results. Temporal discretization was also selectively adjusted.

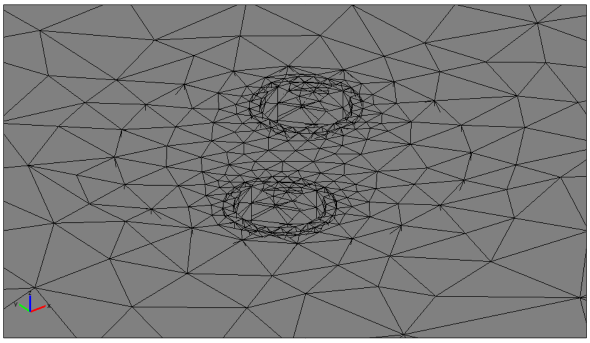

Figure 4: Detail of present Comsol numerical model mesh.

The whole geometry has been finally discretized by means of 400k prism elements obtained by first discretizing the domain radial section with triangular elements, and then extruding the mesh along the axial direction. Particular care was devoted to the discretization of the edges where the weak formulation was applied

A domain mesh snapshot is shown in Figure 4 and some details of mesh features are reported in Table 2.

Table 2: Main finite element model mesh statistics

Model mesh statistics	Value
Number of degrees of freedom	630569
Number of tetrahedral elements	399698
Number of boundary elements	86888
Number of edge elements	16876
Minimum element quality	0.1224

3.2 Validation of the model

The model described above has been validated by comparison with temperature and conductivity results obtained with two finite element models presented by Bauer et al. (2011) and Signorelli et al. (2007) (referred in the following as Bauer model and Signorelli model, respectively) and laboratory measurements presented by Beier et al. (2011) (Beier model here after). Each validation run consisted in setting up the related model with the right set of parameters adopted in the original investigation.. Table 3 summarizes the main parameters related to each model considered in this validation procedure. It must be noticed that even the geometrical parameters has been adapted in order to properly perform the comparison between models. The case presented by Signorelli et al. (2007) consists in fact in a double U pipe while the Beier. setup consists in a squared box filled by sand, with a very compact aspect ratio. Being the geometry of each benchmark case very different, the Comsol geometry was created accordingly for each test case, with dedicated mesh sensitivity analysis which for sake of brevity is not reported here. Bauer numerical model consists in a fully discretized finite element model of a single U pipe BHE and has been modeled in ANSYS Multiphysics in order to validate their resistance and capacity model TRCM (Bauer et al. 2011) and also for recreating a real TRT experiment. Bauer et al. focused the investigation on the effect of the thermal capacity of the grout material with respect to the ground one when a standard ILS analysis is applied. Signorelli et al. (2007) also performed simulations devoted to "virtually" recreate a field test: simulated data were then processed according to standard ILS theory.. The Signorelli model was developed with the code FRACTure (Kohl and Hopkirk, 1995) and the comparisons performed were addressed to a number of open issues concerning TRT like minimum test duration, ground water movement and multilayered ground conditions. In this case the BHE was constituted by a double U pipe. Beier experimental investigation is probably the only study where reference measurements and known thermal properties are available. The measurements in this case refer to a controlled TRT experiment. The experimental setup consists in long box filled by sand where a single U pipe is inserted inside an aluminium cylindrical case. The BHE has a length of 18 m and it is placed in a square section container filled with a known mixture of wet sand.

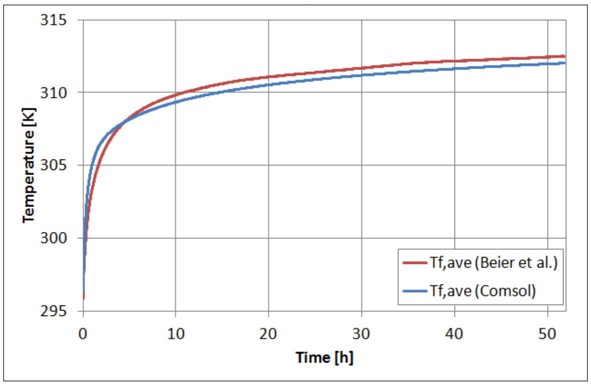

Figure 5: Present model against Beier et al. (2011) experimental results: fluid temperature vs time.

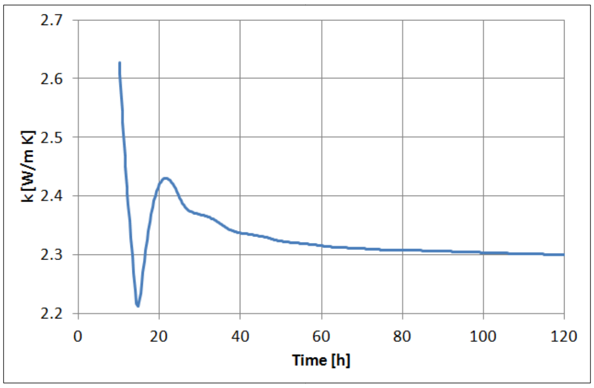

Figure 6: Estimated thermal conductivity evolution with respect to Comsol simulation (Bauer model). ILS slope approach is applied to increasing time intervals.

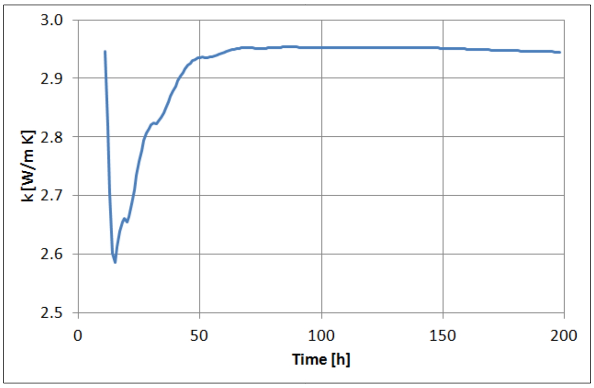

Figure 7: Present model thermal conductivity evolution against Signorelli model parameters. ILS slope approach is applied to increasing time intervals.

The aluminium tube constitutes the borehole wall where the grout filling material and the pipes are placed. Experimental data made available in this study were the fluid temperatures and flow rate evolution, the temperature profiles inside the grout, and temperature measurements at given locations inside the ground (sand) medium. Figure 5 shows simulated and measured fluid temperature vs time in the Beier model. Regarding the back calculation of unknown parameters, the standard ILS approach applied to simulated Beier data yields to k and R_b values equal to 2.90 and 0.157, respectively, in SI units. The same analysis applied to experimental data provides corresponding values equal to 2.91 and 0.161, very similar to those inferred from simulations. Both validations against numerical literature models (Bauer model and Signorelli model) resulted in a good agreement with respect to the back calculation of ground thermal conductivity, as can be observed in Figures 6 e 7.

Table 3: Geometrical parameters, Material properties and working conditions of validator models.

	Bauer model	Signorelli model	Beier model	[Units]
Geometrical parameter				
Scale factor for Comsol model	10	10	2	
Pipe inner radius	0.0163	0.0163	0.0136	m
Pipe outer radius	0.020	0.020	0.0167	m
Borehole radius	0.10	0.076	0.063	m
Shank space	60	60	65	mm
Ground domain radius	3.0	3.0	1.8	m
Borehole length	193.5	160.0	18.0	m
Pipe property				
Specific heat	2400	1800	1800	J/kg K
Density	900	900	900	kg/m^3
Thermal conductivity	0.38	0.40	0.39	W/m K
Grout property				
Specific heat	1095	1000	1000	J/kg K
Density	2000	2000	1500	kg/m^3
Thermal conductivity	2.2	0.8	0.73	W/m K
Ground property				
Specific heat	1110	1390	900	J/kg K
Density	2000	1800	2500	kg/m^3
Thermal conductivity	2.3	3.0	2.82	W/m K
Undisturbed temperature	287.7	285.4	295.5	K
Fluid property				
Specific heat	4200	4180	4180	J/kg K
Density	1000	1000	1000	kg/m^3
Thermal conductivity	0.64	0.60	0.60	W/m K
Working conditions				
Fluid flow rate	0.45	0.37	0.197	kg/s
Fluid velocity	0.54	0.45	0.34	m/s
Convective heat transfer coefficient	1600	1900	1400	W/m^2 K
Heat transfer rate	9645	9000.0	1056.0	W
Inlet/Outlet temperature difference	5.10	3.00	1.28	K

Bauer model considers a ground thermal conductivity value of 2.3 as an input and the back calculation obtained from temperature evolution provided by present model resulted in a perfect agreement when the time interval for regression analysis is the whole one, as can be observed in Figure 6. The same comparison performed considering Signorelli model parameters provided a thermal conductivity (final) value of 2.95 while the Comsol model adopted a value of 3 (Figure 7).

4. CASE STUDIES

As outlined in previous paragraphs, the assumption of constant heat transfer rate during the test is often not verified in field runs. This occurrence may be ascribed to a number of causes, including: non proper insulation of pipes at surface (heat losses/gains from the environment), electrical voltage fluctuations (affecting the heater/chiller performance), unexpected power failures, variations of COP with fluid temperature (cold injection test). The possibility to cope with these non conventional operating conditions is fundamental for assuring reliability of the estimated TRT parameters.

In the following a number of TRT data generated by the present numerical model are discussed and analyzed.
Since standard ILS theory assumptions are not fully satisfied in the case studies here considered, a new approach based on the superposition of the ILS solution itself is proposed.
Temporal superposition is successfully applied for time varying heat loads to the ground, through a description of the variable heat transfer rate as a stepwise function of time. Usually this technique is applied to time steps ranging from months to hours.

In the present analysis the superposition method is employed to subhourly time steps. In the enhanced method the thermal process in the ground is still described by the ILS solution and the thermal interactions inside the BHE by the concept of R_b. The procedure main steps are hence the following: generate a stepwise function describing the history of heat transfer rate to the ground; run ILS superposition with guess values of k and R_b; perform an optimum search analysis aimed at minimizing the average of the absolute values of percentage error between estimated fluid temperature values and measured (in this case "virtually" measured through a Comsol simulation) ones; adjust k and R_b values until convergence. The Comsol model for all the simulations described in this paragraph was run according to the geometrical and thermo-physical properties described in Table 1. As can be noticed, thermal conductivity is set to 2.0 W/(mK).

4.1 Case study #1: data analysis in the "recovery period"

The first case here considered is a situation where the heat transfer to the carrier fluid is stopped after a given amount of hours, while the fluid is still circulated in the BHE. The superposition technique allows the fluid temperature profile to be simulated and described also in the "decay" or "recovery" period, during which further estimates of the ground conductivity can be obtained. Figure 8 shows the heat transfer rate profile vs time together with the average fluid temperature calculated after parameter optimization: final k_{opt} resulted to be 2.04 and corresponding borehole resistance $R_{b,opt}$ 0.122.

4.2 Case study #2: series of heat pulses

This second case is related to a series of power cut off during the test (Figure 9), according to the heat rate profile shown in the same figure. Figure 9 also shows the fluid temperature evolution as calculated in Comsol and the one generated by ILS superposition: after convergence: k_{opt} and $R_{b,opt}$ values resulted equal to 2.04 and 0.120 respectively.

4.3 Case study #3: continuous fluctuation of the thermal power

The third case could describe the effects of the environmental conditions (air temperature, insolation) on the real heat transfer rate to the fluid in a case where for example the pipes outside the ground were not enough insulated. This case could also describe voltage fluctuations on the electric grid, affecting the resistor/compressor performance of the heating/cooling machine. Figure 10 shows the heat transfer profile adopted for this analysis and the final "optimized" temperature profile together with the corresponding Comsol predictions. Optimized k_{opt} and $R_{b,opt}$ resulted in this case equal to 2.06 and 0.122 respectively.

4.4 Case study #4: decay in cooling power

While TRT in heat injection mode is usually carried out by means of an electrical heater or a gas boiler, heat extraction requires a chiller whose cooling power can be affected by the variation of its COP with carrier fluid temperature (and even with environmental conditions). Thus, in this fourth case a heat transfer rate based on a realistic chiller performance has been adopted as the input for the numerical simulation. The COP evolution has been evaluated by means of a fluid temperature trend previously calculated in a simulation with constant heat transfer rate of -50[W/m]. Then the input heat transfer rate was described by a function ranging from -50 to -30[W/m], being the (absolute) lowest value the condition adopted for chiller switch off (Figure 11 green dashed line). In this case while traditional ILS analysis method provides kILS and Rb,ILS values equal to 4.54 and 0.331, optimized k_{opt} and $R_{b,opt}$ resulted equal to 2.10 and 0.128 respectively.

Table 4 summarizes the results of the four case studies presented above with respect to both the traditional ILS approach and the optimization method proposed in this paper. The reference (input) ground conductivity value adopted in numerical simulation is also reported. Since for case #1 (constant heat transfer rate period) a $R_{b,ILS}$ value of 0.118 has been calculated it can be considered the most reliable estimation of this parameter to which to compare the optimization results.

The inspection of Table 4 shows that the superposition analysis is a valuable alternative to ILS standard method in all those cases where the heat transfer rate is not constant and hence where the standard procedure yields not acceptable estimations (study cases 3 and 4 in particular). The optimization method proved to be able to calculate R_b values very close to the reference one (ILS, case #1).

Table 4: Summary of parameter estimations related to case studies 1 to 4: subscript ILS refers to standard TRT analysis while OPT pertains to proposed optimization method.

	#1	#2	#3	#4	Units
k_{gr}	2.00	2.00	2.00	2.00	[W/m K]
$k_{gr,ILS}$	2.05	2.06	2.50	4.54	[W/m K]
$R_{b,ILS}$	0.118	0.120	0.195	0.331	[m K/W]
$k_{gr,opt}$	2.04	2.04	2.06	2.10	[W/m K]
$R_{b,opt}$	0.122	0.120	0.122	0.128	[m K/W]

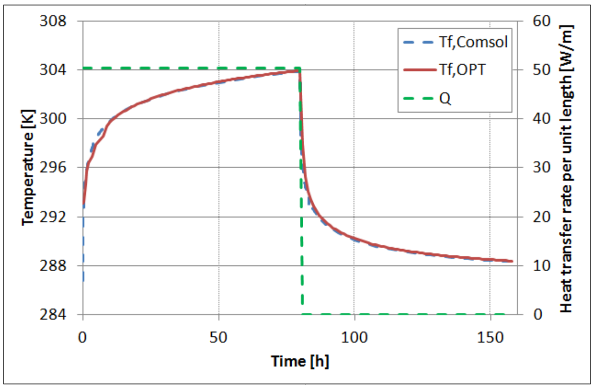

Figure 8: Case Study #1: Temperature and heat transfer rate vs time: Comsol results and present model estimated values (OPT).

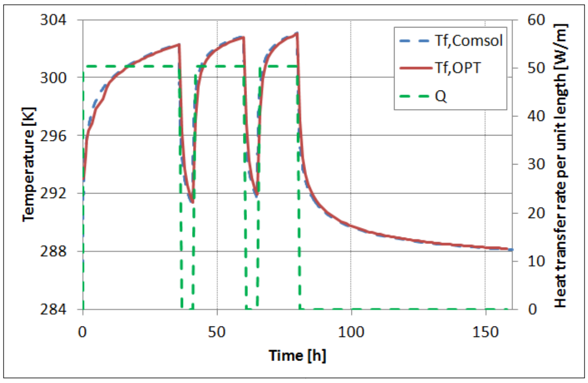

Figure 9: Case Study #2: Temperature and heat transfer rate vs time: Comsol results and present model estimated values (OPT).

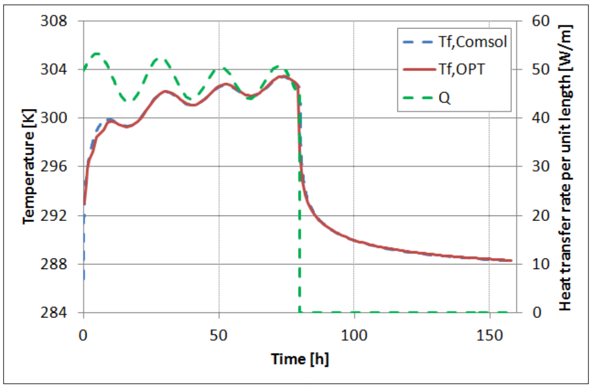

Figure 10: Case Study #3: Temperature and heat transfer rate vs time: Comsol results and present model estimated values (OPT).

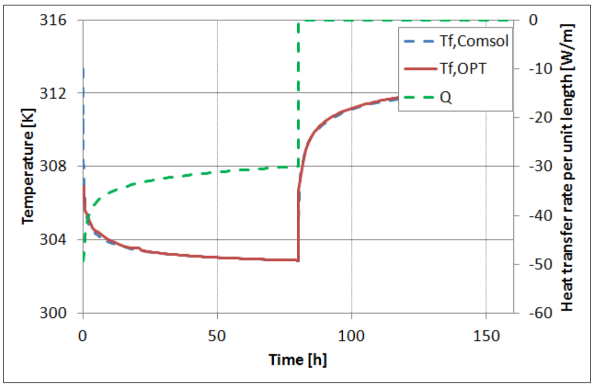

Figure 11: Case Study #4: Temperature and heat transfer rate vs time: Comsol results and present model estimated values (OPT).

5. CONCLUSIONS

In this paper a 3D numerical model for BHE simulation and virtual TRT "experiments" has been presented and discussed. The present Comsol model has been validated against literature TRT data, either obtained in laboratory experiments or simulated with different simulation codes. The present model results proved to be in very good agreement with the literature data. . A number of TRT case studies has been considered in order to focus on situations in contrast with ILS theory assumptions, namely to those conditions where the heat transfer rate to the carrier fluid is considerably varying in time. In order to cope with these operating conditions a novel approach has been proposed and implemented for analysing TRT data. The alternative approach is still based on ILS theory but temporal superposition principles and optimum search analysis are applied. The proposed method proved to be a valuable and reliable tool for estimating either the ground conductivity or the effective borehole thermal resistance.

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