Extraction of Thermal Characteristics of Surrounding Geological Layers of a Geothermal Heat Exchanger by 3D Numerical Simulations

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Abstract:

Ground thermal conductivity and borehole thermal resistance are key parameters for the design of closed Ground-Source Heat Pump (GSHP) systems. The standard method to determine these parameters is the Thermal Response Test (TRT). This test analyses the ground thermal response to a constant heat power injection or extraction by measuring inlet and outlet temperatures of the fluid at the top of the borehole heat exchanger. These data are commonly evaluated by models considering the ground being homogeneous and isotropic. This approach estimates an effective ground thermal conductivity representing an average of the thermal conductivity of the different layers crossed by perforation. In order to obtain a thermal conductivity profile of the ground as a function of depth two additional inputs are needed, first, a measurement of the borehole temperature profile and, second, an analysis procedure taking into account ground is not homogeneous. This work presents an analysis procedure, complementing the standard TRT analysis, estimating the thermal conductivity profile from a temperature profile along the borehole during the test. The analysis procedure is implemented by a 3D Finite Element Model (FEM) in which depth depending thermal conductivity of the subsoil is estimated by fitting simulation results with experimental data. The methodology is evaluated by the recorded temperature profiles throughout a TRT in a BHE monitored facility, which allowed the detection of a highly conductive layer at 25 meters depth.

Keywords:

Ground coupled heat pump; Numerical simulation; Thermal Response Test; Heat transfer; Technic-Economical optimization; Energy efficiency.

1. Introduction

To reduce primary energy consumption and emissions of green house gases, more and more attentions are paid to GSHP as heating ventilation and cooling system (HVAC) to conditioning spaces into buildings and to provide hot water [1, 2, 3, 4, 5]. In general, a typical GSHP system mainly consists of a heat pump, a group of borehole heat exchangers and indoor units. Commonly are coupled with the ground as heat source or sink for exchanging energy by circulation of heat carrier fluid in the tubes of BHEs [6, 7]. The GSHP system takes advantage of subsoil high thermal inertia that remains at a constant temperature, that is more favourable than the outside, so higher energy efficiency can be obtained as compared to traditional air-conditioning systems [8].

The performance of GSHP systems is determined by ground stratigraphy in which thermal conductivity, ground water flow and initial temperature play an essential role [9, 10] Detailed and accurate information of thermal behaviour of subsoil layers crossed by perforation is a prerequisite for improving the ratio between the heat transfer optimization and cost of the installations [11]. Namely, for determination of the maximum heat transfer using the minimum length of the GHE installations.

In order to estimate heat transfer at the vertical BHE, diverse numerical and analytical methods have been proposed from data obtained in field investigation studies [12, 13]. Currently, the more extended method is the TRT based on Infinite Line Source Model (ILS) [14], which describes conductive heat transfer in a homogeneous medium with a constant temperature at infinite boundaries. The TRT consists in applying a constant power input to the soil by a fluid flow inside the pipes and monitoring changes of temperatures at inlet and outlet of the perforation. Mainly two parameters are obtained: effective thermal conductivity, $\boldsymbol{\lambda_{eff}}$, and borehole thermal resistance, $\mathbf{R_b}$, by following theory proposed by Hellström et al. [15]. However, it is difficult to accomplish the optimum design of a GHE and some factors as significant temperature variations produced by weather conditions, pipe insulation, variations in the power source, heterogeneous distribution of subsurface properties… can affect the measuring output of TRT. Additionally, standard TRT measuring output can be considerably affected by the advection effect of groundwater flows and lead to an undesirable deviation of the $\boldsymbol{\lambda_{eff}}$ [16].

Some other studies [17, 18, 19] presented the importance of groundwater flow on improving the performance of BHE and argued that those effects should not be neglected. From the point of view of engineering applications, this enhanced effect is favourable for reducing the possible imbalance between heat injection and extraction from and to the ground, which is helpful for the long-term operation of GSHP systems. For a specific energy demand of a GSHP system, accounting for the axial effects can lower the required length and numbers of boreholes. Marcotte et al. [20] showed for an example design problem that the calculated borehole length could be 15 % shorter when axial effects are considered, which conclusively means a more cost-efficient system. Chiasson et al. [21], Wang et al. [22] and Fan et al. [23] evaluated the effects of groundwater flow on the heat transfer into the BHE. They concluded that groundwater flow enhances heat transfer between the BHE and the aquifer. In this case, shorter or less BHEs are needed for the same technical performance.

In the last decades various investigations have been conducted to reliably calculate TRTs influenced by groundwater flow. One possibility to calculate the influence of groundwater flow is a stepwise TRT evaluation based on the Kelvin line source theory [24]. Witte et al. [25] illustrated an increasing value with increasing evaluation time step size as an indicator for groundwater flow. Another possibility is the suggested analytical solution by Molina-Giraldo et al. [26] based on a Moving Finite Line Source model (MFLS) which takes into account both aspects: groundwater flow and axial effects overcoming the limitations of previous analytical models [27, 28]. The analytical procedure is verified with a finite element model and is concluded that the performance of axial effects essentially depends on the groundwater velocity in the aquifer and the length of the borehole heat exchanger. Some other studies based on the recorded data during the TRT and finite element simulations analysed the importance of natural subsurface conditions, such as vertical geothermal gradients and thermal dispersion [29]. And later, a parameter estimation strategy to calculate information about the actual Darcy velocity based on MFLS was presented by Wagner et al. [30, 31], which is sensitive to conduction and advection.

However, these concepts provide neither information about the exact location of the underground water flow nor information about the depth-depending thermal conductive parameters of heterogeneous ground profiles. For overcoming that, novel strategies are developed based on Distribution Temperature Sensing (DTS) system [32]. In DTS systems, optical fiber thermometer is placed along the inlet pipe of the installation, from which the vertical temperature distribution can be measured. Hence, thermal conductivity of the ground can be evaluated along depth [33]. Fujii et al. [34] performed a comparative study on conventional TRT and the enhanced TRT on DTS. The obtained effective thermal conductivity for both cases is very similar and furthermore, the enhanced TRT indicated the presence of a highly conductive region due to the presence of an aquifer. Wagner and Rohner et al. [35] showed how specific layers with groundwater flow (enhanced λ_{eff} values) can be estimated. Nevertheless, the cost of the required equipment for optical fiber thermometer is high and the process to guarantee the correct placement along the diameter of the pipes can be difficult.

In this research work, an innovative analysis procedure to obtain a detailed depth-depending thermal conductivity profile along vertical BHE subsoil surrounding is presented. The vertical thermal conductivity gradient is estimated from an additional temperature profile along an auxiliary pipe during an experimental TRT and by fitting a 3D finite element model with test results. Likewise, the measured additional temperature profile along an auxiliary pipe by a wired digital temperature probe overcomes the limitations of the methods discussed above.

This paper is divided as follows. Firstly, a BHE built at Universidad Politécnica de Valencia campus of 40 meters depth and composed by six different layers of geological strata is described and the obtained data throughout a TRT of 1 kW are presented. Secondly, the analysis procedure to estimate the thermal conductivity profile of the subsoil layers crossed by perforation based on a finite element model is described. Thirdly, the obtained results after applying the procedure to the recorded data from the performed 1 kW TRT are presented, which allows the detection of a highly conductive layer at 25 meters depth. Finally as conclusions, the obtained results and the hypothetical causes of the discovered thermal conductivity profile are discussed.

Nomenclature:

T_{in}: Water temperature inside inlet pipe
T_{out}: Water temperature inside outlet pipe
T_{avg}: Water average temperature between inlet and outlet pipes
T_{op}: Temperature inside observer pipe
$T_{op}(z)$: Observer pipe temperature related to depth
$T_{op}(z,t)$: Observer pipe temperature related to depth and time
$T_{op\_simu}(z,t)$: Simulated observer pipe temperature related to depth and time
$T_{op\_exp}(z,t)$: Experimental observer pipe temperature related to depth and time

T_{SS}: Near subsoil temperature
T_{ssl}: Far subsoil temperature
R_{pp}: Thermal resistance between pipes
R_{po}: Thermal resistance between pipes and observer pipe
R_{og}: Thermal resistance between observer pipe and near ground
R_{gg}: Thermal resistance between near ground and far ground
R_{bo}: Thermal resistance between borehole and observer pipe
λ_b: Borehole grouting material thermal conductivity
$\lambda_s(z)$: Borehole surroundings thermal conductivity profile
λ_{eff}: Effective thermal conductivity, the mean thermal conductivity of the surrounding subsurface
R_b: Heat transfer between pipes and borehole wall

2. Experimental facility and data

On the Universidad Politécnica de Valencia campus is available a BHE of 40 m depth, 160 mm drill diameter and two geothermal independent pipes ALB GEROtherm PE-100 of 40 mm diameter and, 29 and 39 m long respectively. The pipes are disposed with a turn of 90º between them, keeping uniform the distance between the pipes of the geothermal probes with separators of polyethylene distributed every meter depth. The borehole was drilled by rotopercussion technic with a metallic cylinder contention, which was not extracted during refilling phase. Samples of the subsoil stratigraphy were taken during the drilling to determine composition. In figure 1 is depicted the geological profile and a diagram of the pipes disposal inside drilling and in figure 2 is shown an image of the installation.

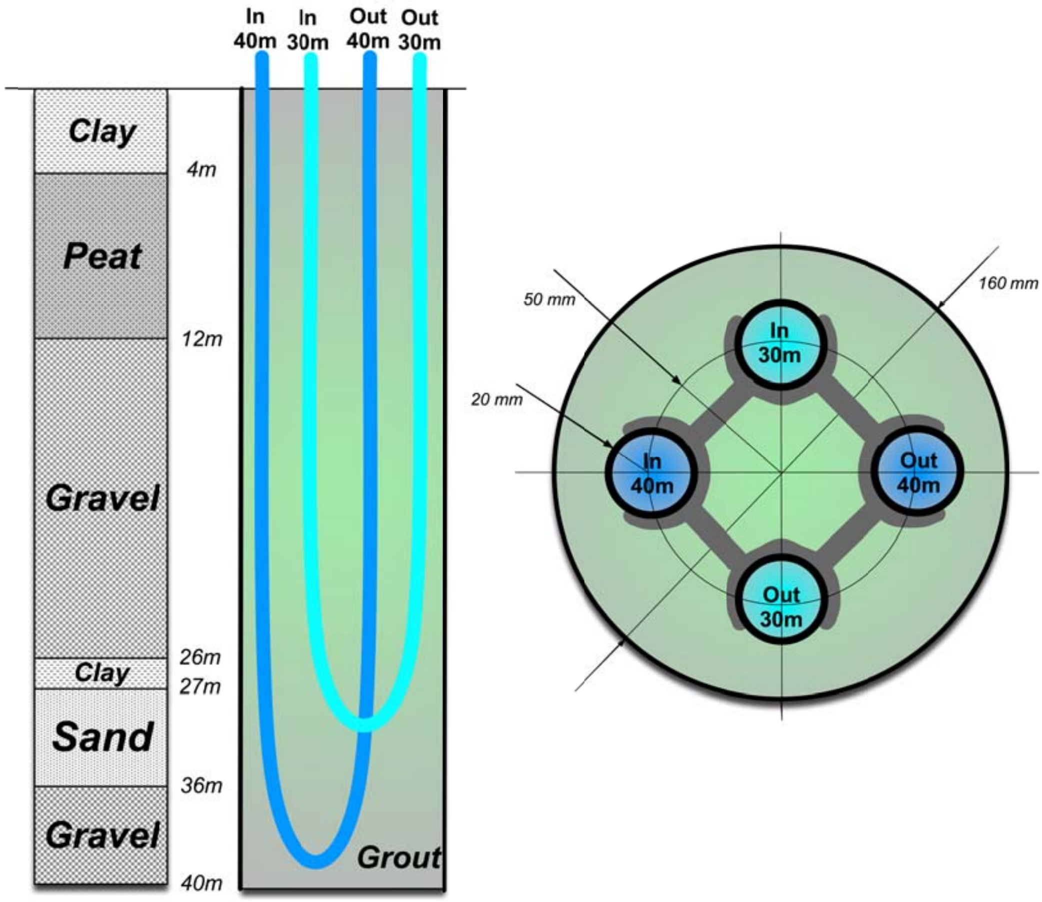

Figure 1. Geological profile and distribution of geothermal probes inside the drilling.

The obtained samples were mixed with water during its transportation and thus were not suitable for an accurate analyse of thermal characteristics of geological layers in laboratory tests. Consequently, only was analysed the dry material and a thermal conductivity that varies between 1.5 W/mK to 2.0 W/mK was estimated from thermal data tables. Besides, from other geological studies performed in 2008 throughout a building construction near the facility, a stratigraphic profile that matched with the samples taken during the drilling was obtained. Specifically, it was conducted by a rotating drilling technique in which samples were obtained unchanged. In the analysis of this stratigraphic column the presence of a groundwater level about 4 meters depth was detected and from samples and laboratory tests a content of moisture between 14 % and 30 % was measured.

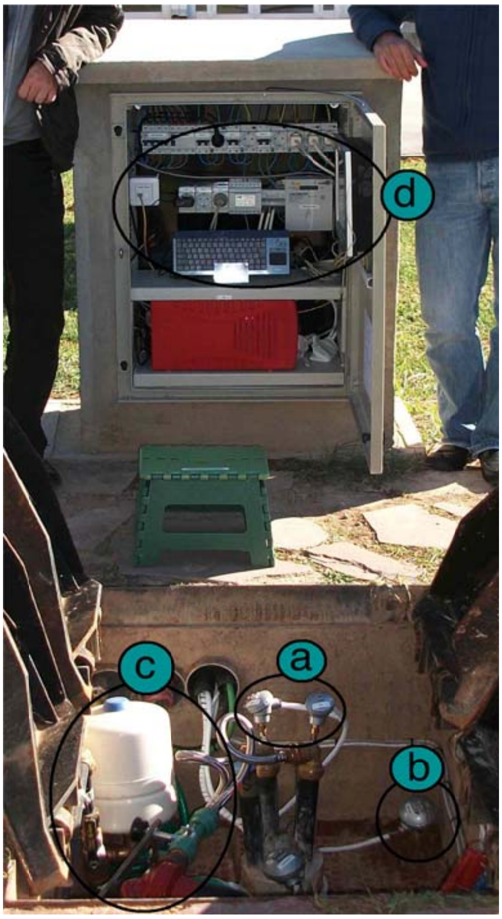

Figure 2. Photography of the experimental installation at UPV Campus. a) T_{in}, T_{out} temperature probes; b) Ground temperature probe; c) Hydraulic subsystem; d) Equipment of control and acquisition.

The drilling filling is done with CEMEX 32.5 raff concrete and bentonite in a proportion of twelve parts of concrete and one of bentonite. This filling solution is suitable for typical Valencian soil, rich in moisture and water flows. The drilling was performed in May of 2010 and during the next months the temperature inside the pipes was monitored in order to determine when the soil recovered its temperature before the drilling. In figure 3 a graph with the inside temperature of the 39 m depth pipes is depicted from its insertion in the exchanger until the stabilization with the surrounding ground, process that lasted about 6 months.

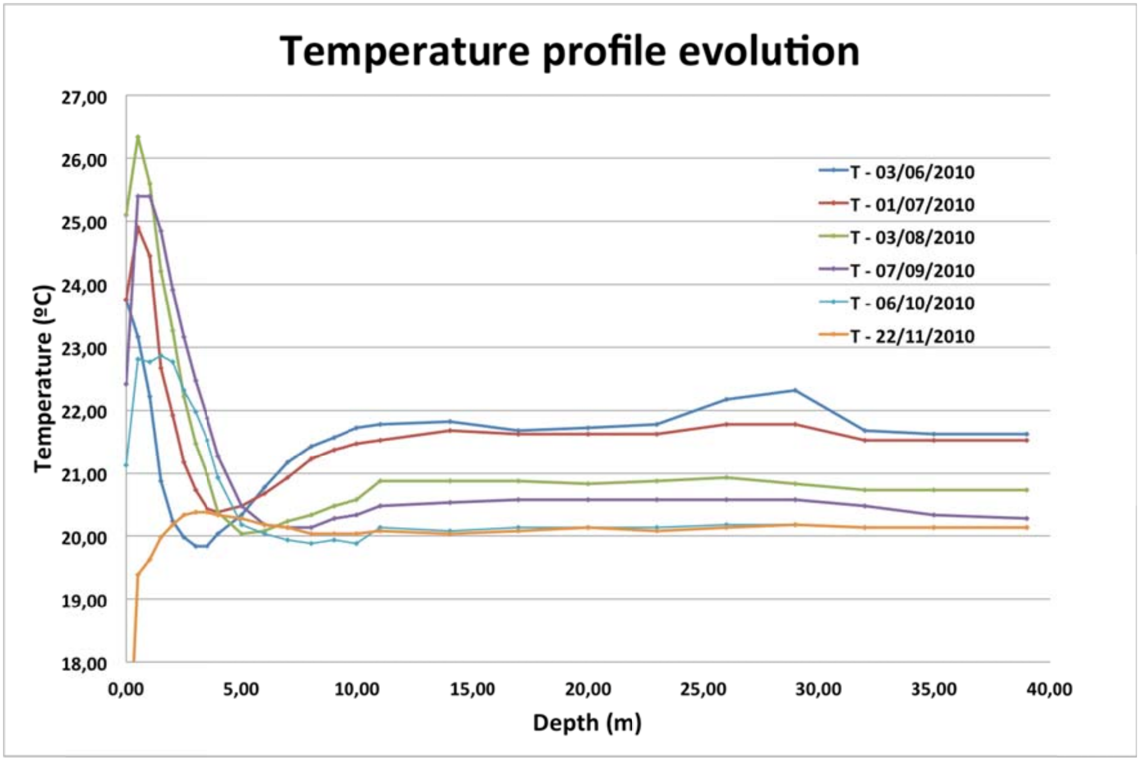

Figure 3. Temperature evolution inside and along the 39 m depth pipe from the insertion date until thermal stabilization.

An equipment to perform heat injection TRT was provided to the installation, consisting of an electronic adjustable circulating pump, a heating resistor of 3 x 1 kW / 220V; a flowmeter; a 5 liters expansion tank; temperature probes at input and output of the exchanger, connected to an acquisition system through a 4 wire 4 – 20 mA loop of TC Direct adjusted in a range from 0 ºC to 50 ºC. The temperature sensors were calibrated through a thermal bath and an electronic precision thermometer, performing a two points lineal adjustment within the dynamic range from 0 ºC to 50 ºC chosen for the sensors.

Furthermore, an energy meter was employed for monitoring electric power source of the installation and a meteorological station for measuring surface environmental temperature and humidity. The full system was managed from a PC with a touch screen and Internet access that performed acquisition and register of the data during the TRT, through a program developed in Matlab.

On 9th March 2011 at 11:00 a 1 kW heat injection TRT was started, using the geothermal pipe of 29 meters length, and leaving the one of 39 meters filled with water in order to use it as an observer pipe and measure the temperature profiles during the TRT. A flow of 410 l/h of water without glycol was fixed, and the PC program was configured to acquire data with a 3 minutes period. The test lasted 3 days, with an environmental average temperature of 10.6 ºC, oscillating between the maximum of 18.1 ºC and the minimum of 6.5 ºC. Figure 4 depicts the temporary evolution of environment temperature and temperature evolution at inlet (T_{in}) and outlet (T_{out}) of the TRT during 3 days. Temperature profiles at inlet and outlet show some fluctuations that correspond to the environment temperature variations during the test realization.

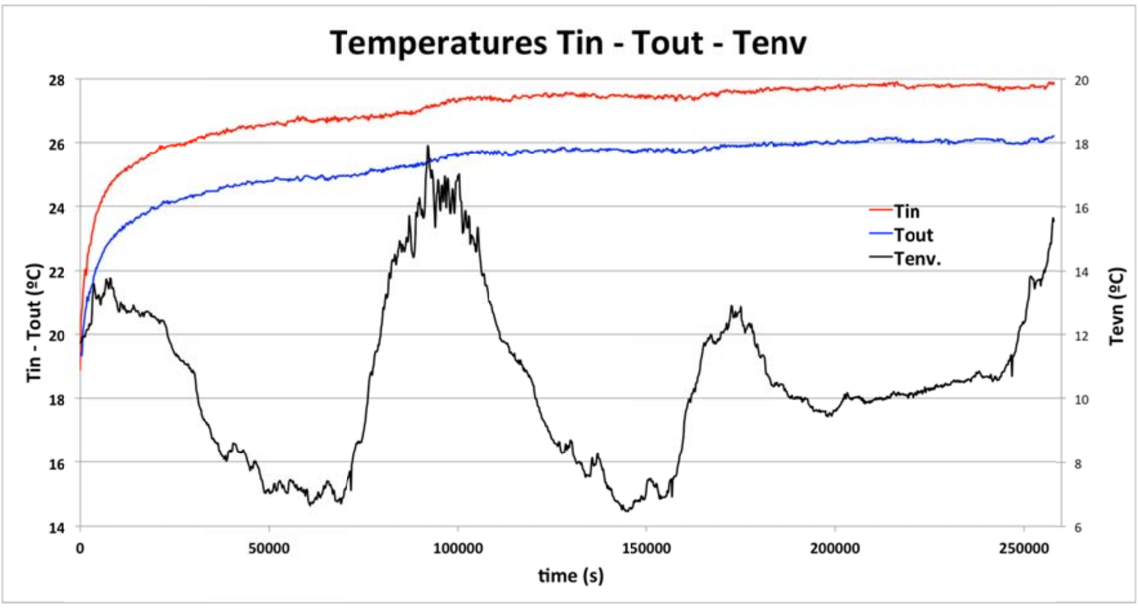

Figure 4. Inlet, outlet and environment temperature evolution during the analysed TRT injection of 1 kW.

An approximation of the effective thermal conductivity parameter of the ground was calculated applying the ILS model of Kelvin [36] to the obtained experimental data during the TRT. Figure 5 shows two straight sections that give higher conductivity estimation for the final test hours than for the first test hours, deviating from the ILS model prediction. The observed behaviour is typical scenario of areas with presence of moisture or water flows produced by the greater heat absorption of the layers affected by groundwater flows. In this case the turning point is placed at 10 hours from the beginning of the TRT and the last stretch based on TRT sizing gave a borehole resistance of 0.12 K/W and a conductivity of 2.41 W/m K.

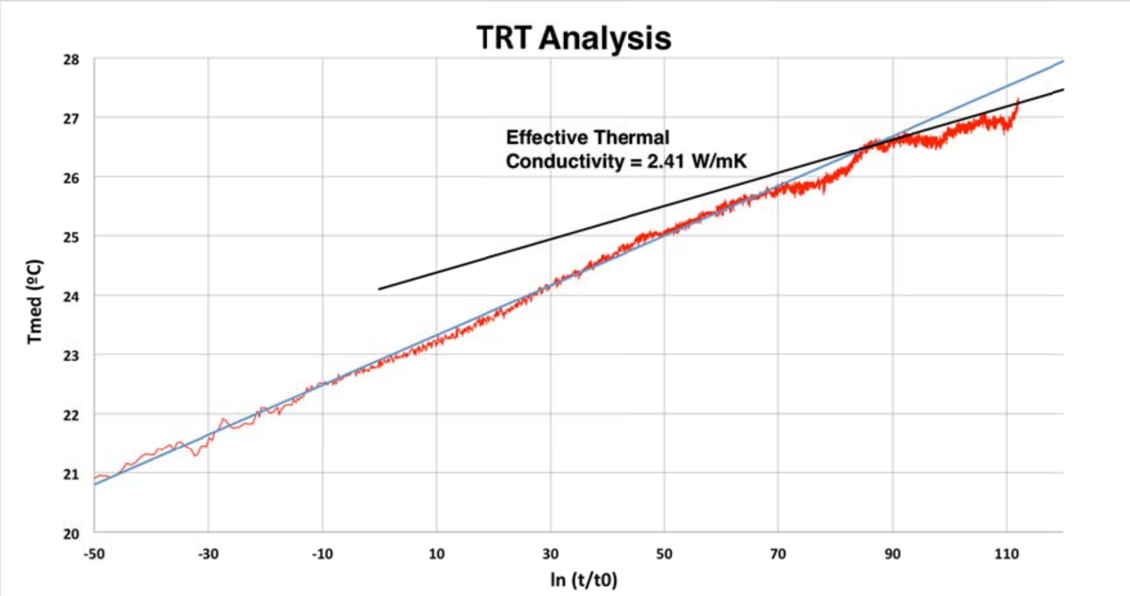

Figure 5. Semilogarithmic representation of the average fluid temperature $T_{in} - T_{out}$ as a function of the variable x during a TRT injection of 1 kW and the calculated effective conductivity.

Additionally, from the beginning of the TRT the temperature profile was obtained in one of the 39 meters length pipe, which was not used in this TRT for heat exchanging and named before as observer pipe. The measured data are depicted in figure 6. Each coloured marked line corresponds to a temperature profile along the observer pipe through time from 9th March (start of TRT) until 12th March (end of TRT). Furthermore, the five dashed black lines show the edges between geological strata determined by the obtained samples during the drilling.

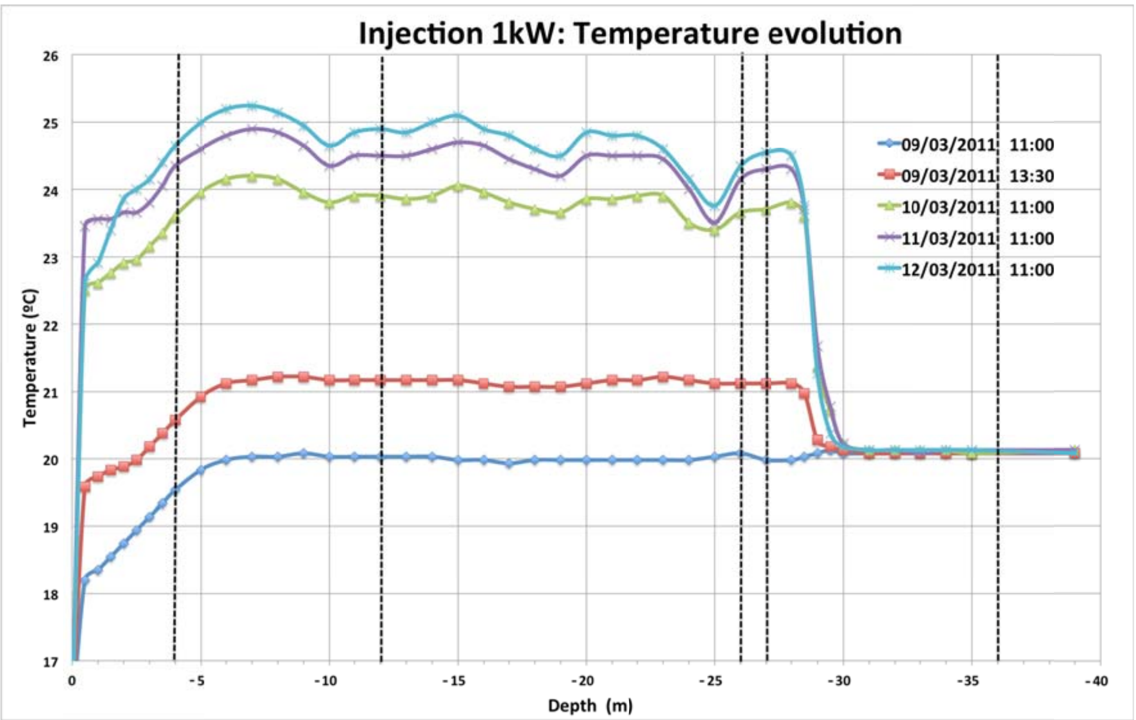

Figure 6. Temperature profiles along the observer pipe during the analysed TRT injection of 1 kW. Coloured marked lines: five temperature profiles taken from 9th March to 12th March. Dashed lines: edges of geological layers determined during the drilling.

To obtain the temperature data inside the observer pipe, a waterproof sensor was connected to an end of a 50 m length cable. This wired digital sensor only requires 2 wires for the connection and it transmits temperature data in digital format, reducing the errors that could be produced due to the cable length. The accuracy of the measurement is 0.5 ºC in the range from -10 ºC to 85 ºC, and it has a maximum resolution of 12 bits, thus a temperature resolution of 0.0625 ºC is achieved.

The process of obtaining a temperature profile consists in descending the sensor at prefixed depths of 0.5 meters in the first 4 meters of the drilling, and at 1 meter between the 5 meters and 28 meters depth. Then again at 0.5 meters between 28.5 and 30.5, ending the descent with 1 meters gaps. At each measuring point, the sensor was held in position for 5 seconds for thermal stabilization, before new temperature data was taken at the next depth. A temperature profile disturbance was created as the sensor was lowered but it was not taken into account due to its small size (<5 mm ø). This sensor was also calibrated with the same equipment used with the temperature sensors disposed along the rest of the installation.

After a careful drilling execution, insertion of geothermal probes and filling process, a borehole with the same thermal characteristics for the whole volume was built. Therefore, the measured temperature variations inside the observer pipe will be due to the conductivity values of geological layers. And heat transfer between the borehole and the subsoil can be evaluated.

3. Procedure to estimate thermal conductivity

The aim of this research work is to estimate the thermal conductivity profile of the borehole surrounding layers crossed by perforation, from the registered data throughout the execution of a TRT. Due to the fact that TRT considers the medium homogenous, and heat transmission in solids as a mechanism of diffusion, an infinite set of subsoil conductivity profiles ($\lambda_s(z)$) would generate the same set of data for the recorded T_{in} and T_{out} during the execution. Additional information is necessary in order to restrict the possible set of thermal conductivity profiles to only one. In this approach, the data that will impose the last restriction is taken as a series of vertical temperature profiles inside the filling of the exchanger, measured in determined time periods ($T_{op}(z,t)$). In addition, only heat transmission in solid will be considers as heat transfer mechanism.

If an exchanger is analysed by the model of thermal resistances and capacitances, across section of a BHE can be depicted by a delta network [37], such as the one in figure 7a.

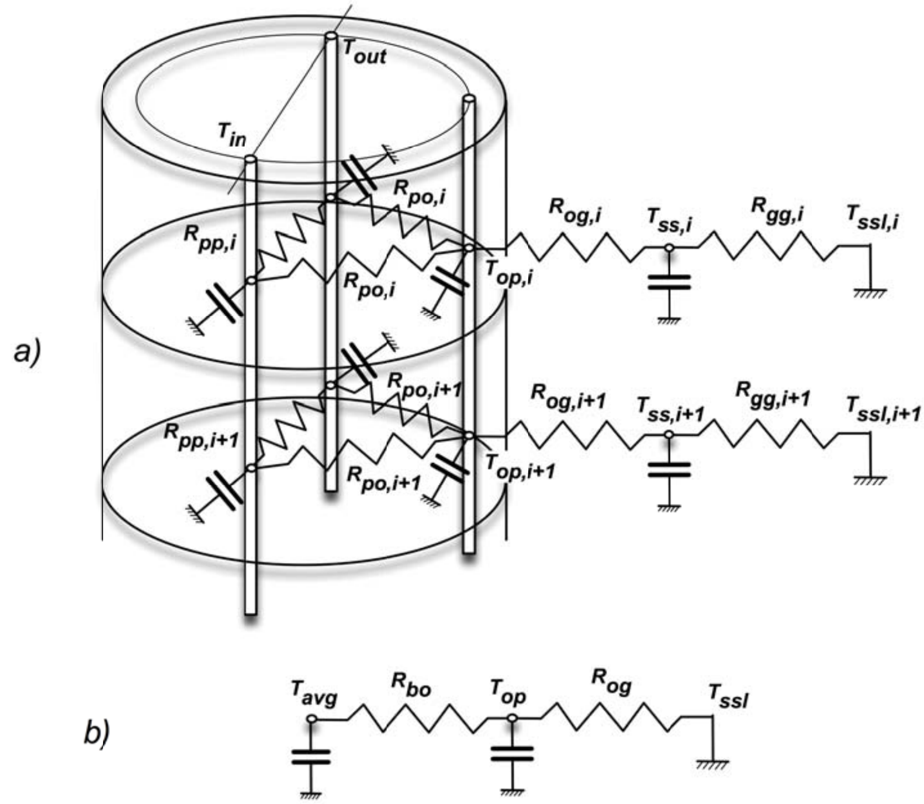

Figure 7. a) Resistances and capacitances model by delta network across a section of a BHE. b) Previous model simplification by an equivalent circuit

This network can be simplified by an equivalent circuit formed only for 2 resistances and 2 capacitances, as is shown in figure 7b. If a carefully BHE construction is performed, R_{bo} will be constant in all the domain of the grouting material and R_{og} will vary its value accordingly to the thermal characteristics of the geological layer for which is surrounded.

Thus, the temperature ($T_{op}(z)$) will change in function of R_{og} resistance that is dependent on the conductivity of the subsoil.

In this approach, a 3D finite element model simulation is employed, in order to adjust a series of temperature profiles taken inside the borehole ($T_{op}(z,t)$). The procedure is initiated by assigning the effective thermal conductivity obtained from the TRT to both borehole and subsoil, and is performed a simulation of the TRT. Once the simulation is finished, the obtained temperature profiles are compared with those measured during the experimental TRT, and thermal conductivity of the subsoil is modified based on the following algorithm:

If max(abs($T_{op\_simu}(z,t) - T_{op\_exp}(z,t)$)) > ε

If ($T_{op\_simu}(z,t) < T_{op\_exp}(z,t)$) **then** increase $\lambda_s(z)$

If ($T_{op\_simu}(z,t) > T_{op\_exp}(z,t)$) **then** decrease $\lambda_s(z)$

Start a new simulation

Else Simulations are completed

Namely, it will be conducted as many simulations and adjustments of thermal conductivity profiles $\lambda_s(z)$ as it will be necessary for reaching an error smaller than the desired value between the measured temperature profiles during the TRT and the obtained during the simulation. The resultant conductivity profile is taken as the one that represents the subsoil surroundings of the exchanger.

4. Application of the procedure to an experimental TRT

In this paragraph the previously elaborated procedure is applied to the recorded data from the experimental TRT of 1kW heat injection described before. A 3D finite element model with the same geometry of the experimental BHE is developed using COMSOL Multiphysics ® version 4.4. Then, the model is adjusted to fit with the measured data in order to estimate the thermal conductivity profile of the borehole surrounding layers.

From all the modules available, the Heat Transfer in Solid (ht) and Non-Isothermal Pipe Flow (nipfl) have been used.

The simulations have been completed under following conditions:

- Only heat transmission in solid has been considered into borehole and surroundings (convective effects has been neglected).
- Thermal parameters of borehole grouting materials have been considered constants, λ_b = constant, Cp = constant, ρ = constant.
- Thermal conductivity of surrounding has been defined as depth dependent, $\lambda_s(z)$, and has been adjusted in order to fit the temperature profile into observer pipe.

In order to simplify computer operations and to reduce the calculation time, a symmetry plane defined by the pipes that form the U of the exchanger has been considered, which has reduced the total volume of the model by half. In figure 8 is presented the resultant model after applying symmetry, in which is possible to appreciate the two contained domains as two concentric cylinders. The smaller cylinder of 0.08 m radius, represents the perforation filled with the grouting material in which the U pipes are inserted, and the other cylinder of 0.75 m, the subsoil volume in which the heat is transferred. Looking for the optimal volume to simulate the borehole, two models were built with different subsoil radius, one of 0.75 m and another of 1 m. The obtained results for both models were very similar, with a maximum difference of 0.083 ºC and a relative error of 0.03 % in both measured points (T_{in} and T_{out}). After, another model of radius 0.6 m was built and compared with the model of 1 m radius obtaining an absolute error of 0.235 ºC and a relative error of 0.9 %. Thereby, the decision of employing a 0.75 m radius for subsoil volume was taken due to the model simplicity and behaviour similarities. Since symmetry onto XZ plane has been used the final model is displayed shaped as a 30 meters length semi-cylinder. In table 1 the configuration data of the developed 3D model can be appreciated.

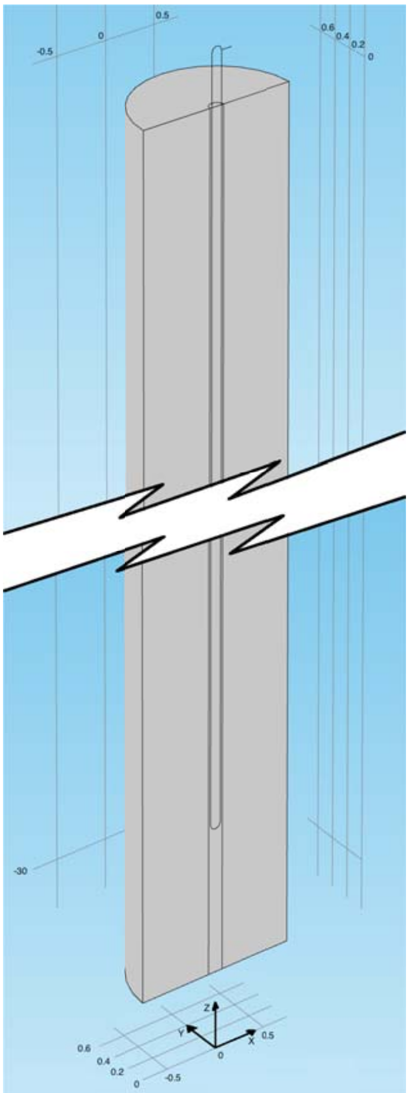

Figure 8. 3D model of the experimental exchanger implemented in COMSOL Multiphysics 4.4.

Parameter	Value
Borehole depth	30 m
Borehole radius	0.08 m
Outer radius of U-tube pipe	0.02 m
Inner radius of U-tube pipe	0.016 m
Centre to centre half distance	0.06 m
Pipe thermal conductivity	0.6 W/m K
Pipes length	29 m
Ground radius	0.75 m
Ground deep	30 m

Table 1. Simulation parameters.

After establishing a finite geometry, both domains were defined with equal characteristics assigning the effective conductivity of 2.41 W/m K obtained during the last stretch of the realized experimental TRT.

Therefore, for the first simulation both domains were configured with a thermal conductivity of 2.41 W/m K, a density of 1800 kg/m^3 and a specific heat capacity of 2000 J/kg K. The simulation was set up using an injected power of 950 W and a caudal of 420 l/hour. The initial temperature value of the topsoil was established as the recorded average value of 16 ºC throughout the days of the TRT implementation. As well as, the layers of the ground were initialised with the obtained temperature values along the observer pipe before the beginning of the TRT.

Another important factor that directly affects to the simulation time and accuracy is the model meshing. Some simulation trials were run with different user-defined meshing configurations until the most suitable solution was found in the simplest model as less time was used in converging to a solution without lose accuracy in the results. Finally, a model meshing with a maximum size of element of 0.25 m, a minimum size of 0.03 m, a factor curvature of 0.3, a narrow regions resolution of 0.85 and a maximum growth of 1.35 elements was selected. With those parameters, 423.256 tetrahedral elements for model domains were obtained. Another model composed of 684.863 elements was built and simulated in order to check if the accuracy was improved but, after comparing both results, an absolute error of 0.005 ºC and a relative error of 0.05 % were obtained. A third model with 265.088 elements was built obtaining an absolute error of 0.013 ºC and a relative error of 0.05 % compared to the model of 423.256, but with similar simulation time. In consequence the decision of employing a model with 423256 elements was taken.

Temporal parameters of simulation were established as follow: total simulation time of 3.1 days, maximum step of 100 seconds and data registration every 20 minutes.

Then, the calculated effective thermal conductivity from TRT datasets were adjusted to both domains and, the first simulation was conducted. In figure 9 the obtained T_{in} and T_{out} temperature profiles from simulation are presented in superposition with the recorded data during the experimental TRT. Additionally, in a similar manner, in figure 10 is depicted the superposition of simulated temperature profiles and the obtained ones along the observer pipe during the experimental TRT.

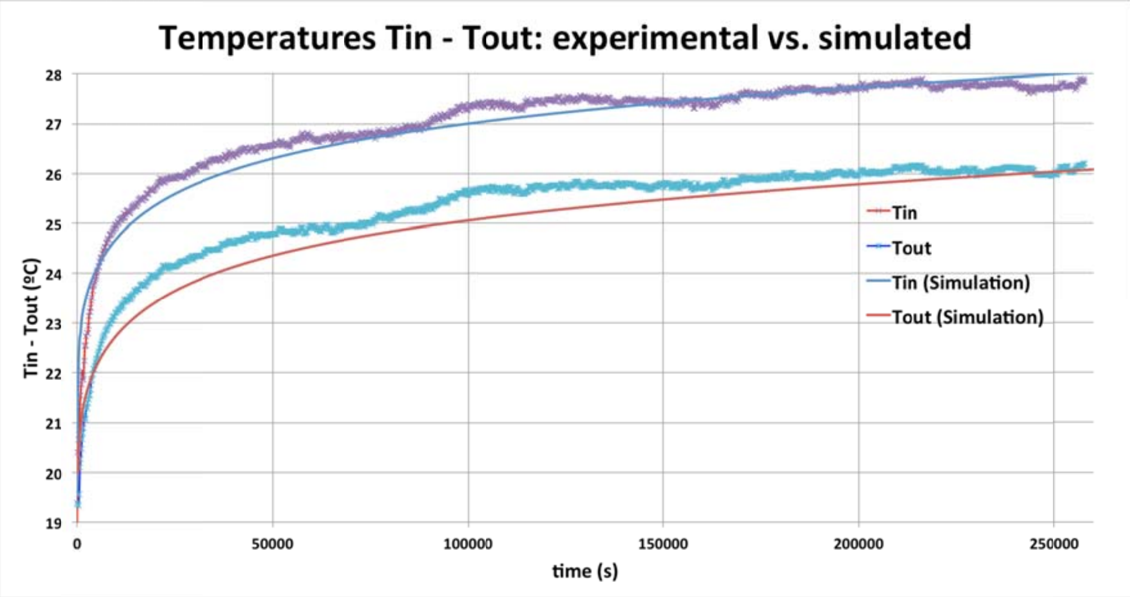

Figure 9. Superposition of $T_{in} – T_{out}$ temperature evolution during a TRT and the obtained ones in the initial simulation. Experimental data (thick lines) and temperature simulation (thin lines).

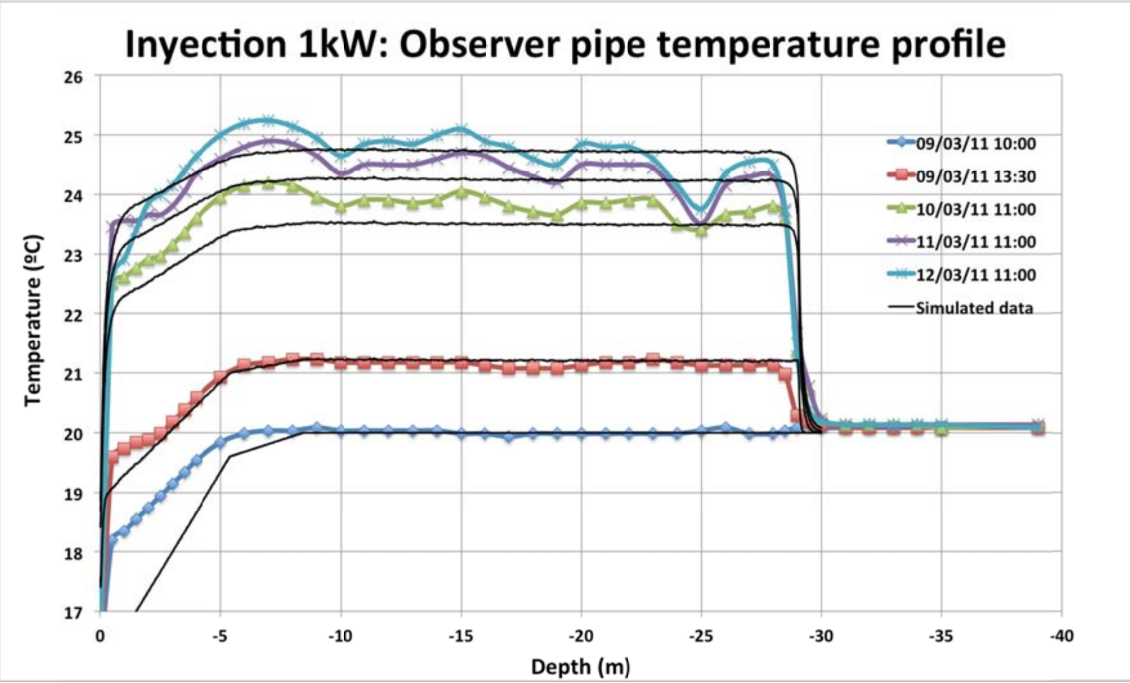

Figure 10. Superposition of experimental data along the observer pipe and the obtained data from the initial simulation. Experimental data (colored marked lines) and temperature simulation (black lines).

The next phase of the simulation was implemented by adjusting the conductivity values of the subsoil. Following the proposed analysis procedure, the model adjustment was continued with the iterative set of simulations. In this case, a maximum temperature value between samples of 0.3 ºC was selected because the error in the sensor measurement range from 20 ºC to 25 ºC is bounded between 1.5 % and 1.2 %, which was considered acceptable in our approach. After a few iterations, was possible to get an improvement in the adjustment between the experimental TRT data and simulation results, maintaining the correspondence both in the evolution of the temperatures T_{in} and T_{out} and in the observer pipe, as is presented in the graph of figure 11.

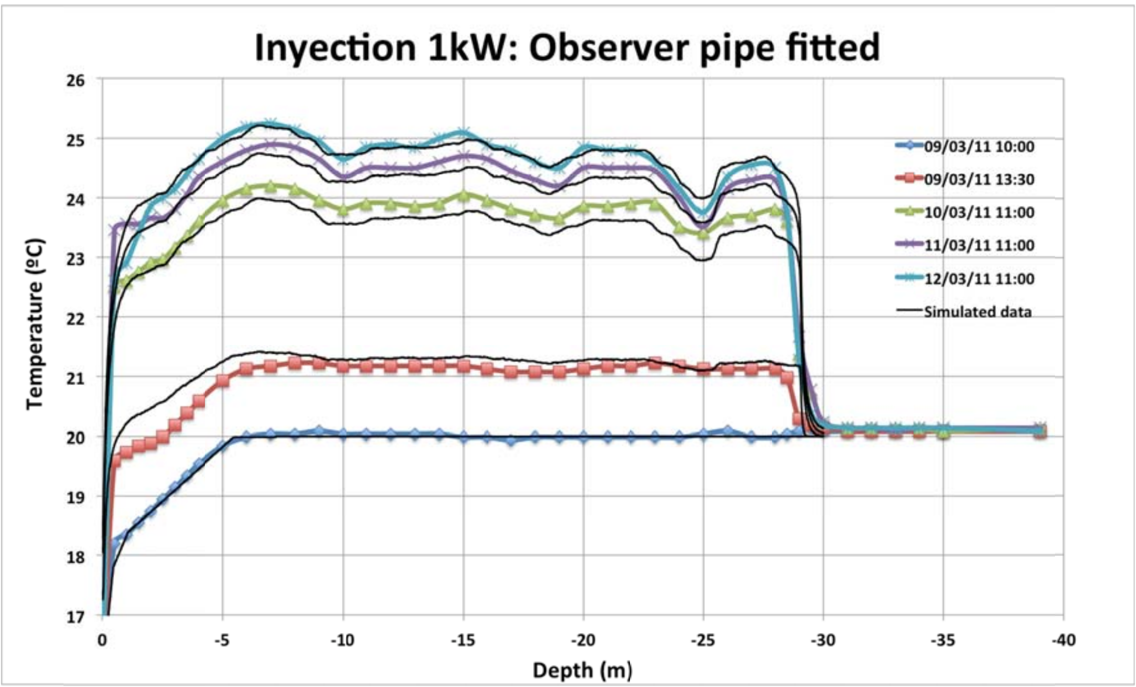

Figure 11. Superposition of temperatures profiles evolution along the observer pipe during the TRT and the obtained results from final simulation. Experimental data (colored marked lines) and temperature simulation (garnet lines).

Besides, in figure 12 is shown the resultant adjusted thermal conductivity distribution along the vertical subsoil layers from the last simulation (using the best achieved settings). It is noteworthy to observe the high conductivity layers located between the 24 and 26 meters depth.

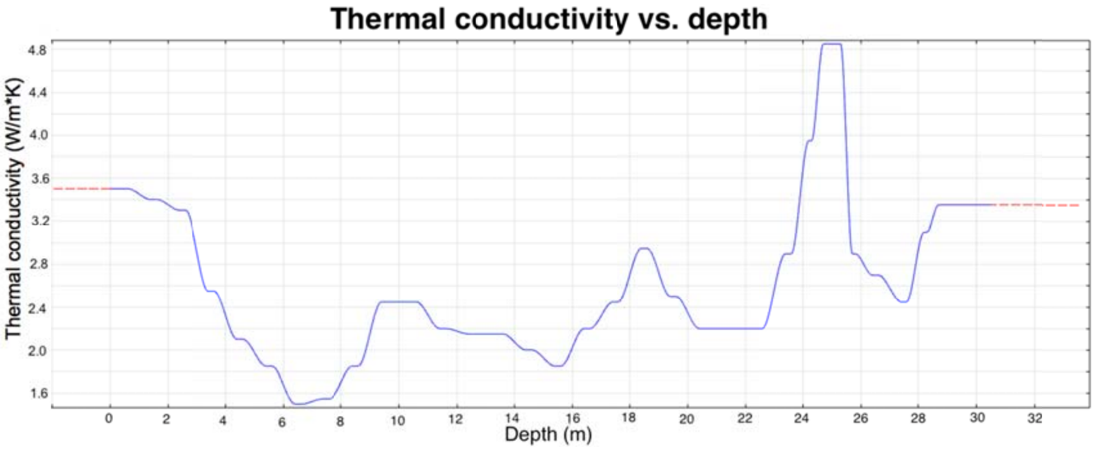

Figure 12. Conductivity profile in the geological layers of the subsoil obtained from simulation.

Moreover, two heat injection TRT of 2 kW and 3 kW were conducted over the same installation, on 22nd November 2010 and on 15th December 2010, respectively. In those tests it was not registered the observer pipe temperature profiles with enough spatial and temporal resolution, so it was not possible to perform the same procedure described above for obtaining the subsoil conductivities profile. Although, aiming to test the developed 3D FEM with more experimental data and different heat sources, the recorded $T_{in} - T_{out}$ temperature profiles for the TRT of 2 kW and 3 kW were compared with results from simulation. For that, two simulations were carried on over previously adjusted model, one with a power of 2 kW and other with a power of 3 kW. The comparison between obtained simulation values and the registered in the TRTs are depicted in figure 13, which presents a quite accurate adjustment.

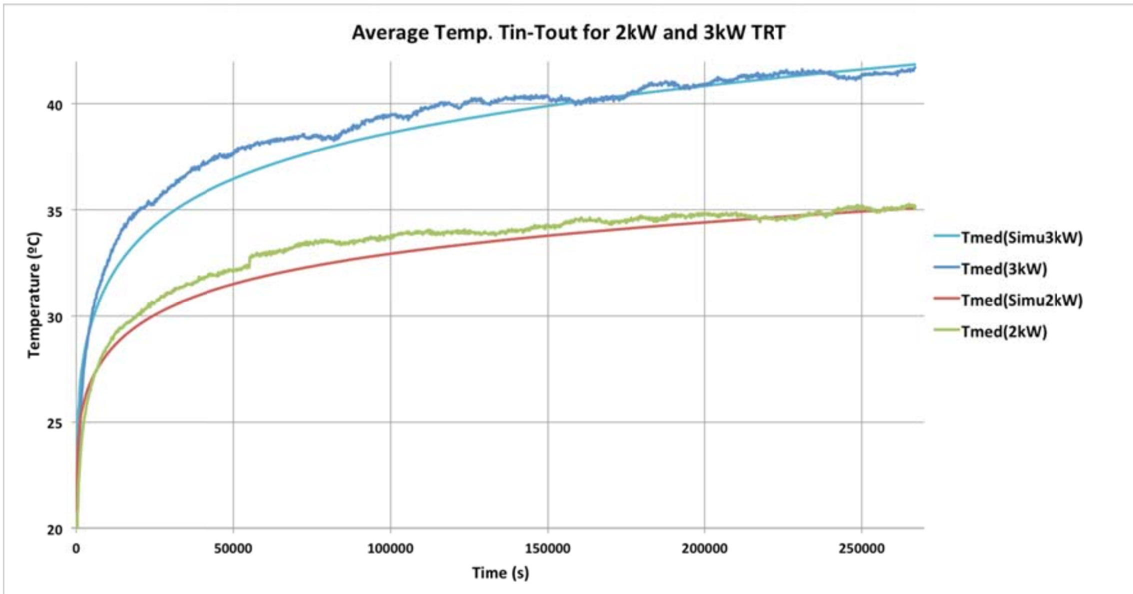

Figure 13. Superposition between the obtained data in experimental TRT for 2 kW and 3 kW between the obtained results from model simulation.

5. Conclusions

One of the main findings of this research work is the estimated conductivity profile of geothermal layers crossed by perforation from the results of a 3D finite element model simulation. The presented novel temperature profile is an additional measurement that can be implemented in combination with the conventional TRT enhancing the obtained results. This methodology does not require samples of ground stratigraphy and has been possible to obtain a thermal conductivity profile of the subsoil by the recorded data during the suggested enhanced TRT. Furthermore, the calculated effective thermal conductivity of 2.41 W/m K during the experimental TRT agreed with the obtained value from simulations, demonstrating the applicability and reliability of the testing and data interpretation methods. Also, the recorded U pipe inlet and outlet and observer pipe temperature profiles during the experimental TRT are very similar to the achieved results from simulation.

The obtained thermal conductivity profile presents an accurate adjustment of the temperatures along the observer pipe, except for a region located between 24 and 26 meters that may be caused by the groundwater advection effects. The development of a new model in which conduction and advection are taken into account will likely improve the obtained results. In such case, more detailed information of the axial effects can be interpreted, as for example, an estimation of the location and the velocity of underground water flows.

To sum up, the proposed enhanced TRT and the analysis procedure are validated as a useful method to identify the position of the groundwater flow in a borehole subsoil surroundings. The location of groundwater flow can help to improve heat transfer efficiency of BHE. Therefore, the obtained data could easily parameterize the length of the drilling for implementing a totally optimized heat exchanger in order to maximize the W/m relation of the thermal transfer. The findings of this study will provide valuable information for thermal conductivity measurements in field and will improve the performance analysis of BHE in layered subsurface.

Acknowledgments

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