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Research Paper

Extraction of thermal characteristics of surrounding geological layers of a geothermal heat exchanger by 3D numerical simulations

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HIGHLIGHTS

- An innovative analysis procedure, complementing the standard TRT analysis.
- A novel temperature profile is presented as an additional measurement during the TRT.
- Estimate thermal conductivity profile of geothermal layers crossed by perforation.
- Implemented by fitting 3D FEM simulation results with experimental data.
- Allowed the detection of a highly conductive layer in an experimental BHE installation.

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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 (Borehole Heat Exchanger) monitored facility, which allowed the detection of a highly conductive layer at 25 meters depth.

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 [1–5]. In general, a typical GSHP system mainly consists of a heat pump, a group of borehole heat exchangers and indoor units. Commonly, these are coupled with the ground as a heat source or sink for exchanging energy by the circulation of a 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,

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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, $\lambda_{\mathbf{eff}}$, 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 $\lambda_{\mathbf{eff}}$ [16].

Some other studies [17–19] 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, a 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 fibre 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 fibre 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 allow 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.

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 90° 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 technique 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 Fig. 1 is depicted the geological profile and a diagram of the pipes disposal inside drilling and in Fig. 2 is shown an image of the installation.

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 the dry material and a thermal conductivity that varies between 1.5 W/mK and 2.0 W/mK was analysed and 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.

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