

Device Modeling for GHE Experimental Test

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Abstract. Ground Thermal Response (TRT) tests are employed to calculate ground thermal characteristics for Ground Heat Exchanger (GHE) design and optimization purposes. There are plenty of 3D models to increase the accuracy of the calculated characteristics, with which the fluid outlet temperature is obtained based on the experimental inlet temperature. To simulate other behaviours not tested in the GHE, it is necessary to correctly simulate the conduct of the fluid inside the test equipment. For this reason, a simple model has been obtained which considers the absorption of heat by the elements of the equipment during an initial time through a variable equivalent heat capacity term and a load factor.

Keywords. Ground Heat Exchanger (GHE), geothermic, mathematical model, equivalent heat capacity, Thermal Response Test (TRT).

1. Introduction

The TRT tests allow the evaluation of the thermophysical characteristics of the ground surrounding a GHE, in order to later design or optimize a GSHP installation [1, 2]. A very precise way to assess these characteristics is through 3D numerical modelling [3-5], particularly on vertical elements. The values of those parameters are considered adequate when, at each time step, the simulated outlet temperature of the GHE fluid is similar to the experimental one, approximated with a minimum adjustment error. Among the input variables to carry out each simulation, the inlet temperature of the fluid to the GHE is needed, which is also measured in the TRT test [6].

Model validation is usually achieved by simulating other experimental tests [7] or conducting laboratory tests of ground materials [8]. Subsequently, it is viable to simulate the performance of the same GHE under other conditions, with an inlet fluid temperature profile that can be totally different, and other time intervals. It is even possible to assess and model another GHE based on the original, with different geometry, since there is great interest in studying the GHE for different depths [9]. In any case, and since the process would be completely simulated, a way must be

found to synthetically generate the fluid inlet temperature to the GHE in the new situation. This means, knowing the behaviour of the system that supplies (or takes) heat to the heat transfer fluid outside the GHE, in such a way that it allows estimating that temperature based on knowledge of the GHE fluid outlet temperature at the previous time instant.

In this sense, a first approximation would be to simulate the heating process of the fluid in the device itself that performs the TRT test. The procedure consists of generating a model of the device, which uses the fluid temperature at the GHE outlet (device inlet) at a given time step, to establish the fluid temperature at the GHE inlet (device outlet) at the next step. Said model may be validated with the experimental data of the same TRT trial.

In this first approach, we seek to develop a simple model that can be integrated into the 3D model of the GHE, and that involves the least possible computational load. Consequently, the device is evaluated as a thermal deposit, whose temperature is permanently changing. This simple model does not consider the temperature distribution of the fluid along the path of the device, so that, in order to be effective, the equivalent thermal capacity parameter, which is variable in time, is searched to simulate the mentioned performance.

The aim of this work is to analyse the influence of both the behaviour of the device (through the instantaneous load factor of the electrical resistance that supplies the heat flow to the water) and its materials in contact with the water (thermal inertia of pipes, tank and so on) on the inlet temperature of the fluid to the GHE, in a TRT test. Thus, it is developed an equation which considers the heat exchange inside the device to the water as well as to its internal elements at the beginning of the tests. This equation will be introduced in the 3D model of the GHE, so that the model can generate the input data to the GHE from its output data (previously the input data introduced were experimental).

2. Materials and Methods

A. Experimental facility

In this study, the equipment used to carry out the TRT test consists of a hydraulic system connected to a 130 m deep U-shaped geothermal probe, through which the fluid is recirculated with a selected flow rate, as shown in Fig. 1 [10]. It is composed of sensors installed at the inlet and outlet of the device, which are responsible for measuring the variables of interest (pressure and temperature), in short time intervals in order to ensure high accuracy. Inside the equipment there is an electrical resistance responsible for heating the fluid as it passes through, which aims to constantly supply a heat flow, $\dot{Q}_{w0}$, throughout the test, consuming the same amount in the form of electrical energy, $\dot{W}_{e0}$.

The experimental procedure is composed of two steps: first, an Undisturbed Ground Temperature Test (GTT) was performed [11], obtaining a temperature profile T_s as a function of depth. Subsequently, in a three-day TRT test, selecting a flow rate of 15 l/min and a constant heat output $\dot{W}_e = \dot{Q}_{w0}$ of 4000 W, the temperature of the inlet and outlet fluid was determined (Fig. 2). With these temperatures and applying the infinite line method (ILS) [12], the conductivity of the ground, λ_s , and the constant value of the thermal resistance of the borehole filling material, R_b , can be calculated [13].

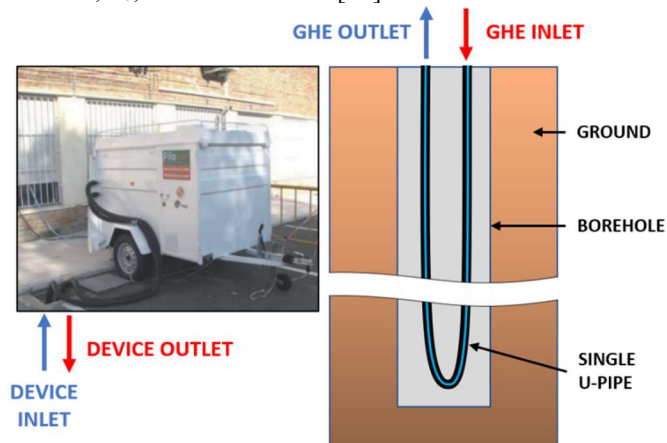


Fig. 1. Disposition of GHE.

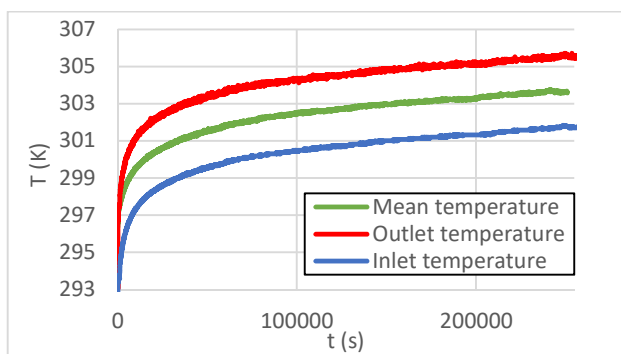


Fig. 2. TRT test temperatures

However, it is essential to consider that the system controls $\dot{W}_e(t)$ so that the heat flow supplied to the fluid, $\dot{Q}_w(t)$, approaches closely the set value $\dot{Q}_{w0}$ for the test, therefore,

the control system adapts $\dot{W}_e(t)$ at all times. This consideration implies that there is heat storage, both in the device and in the fluid itself, realizing that $\dot{W}_e \neq \dot{Q}_w$. The load factor, F_q , is defined as the ratio between $\dot{W}_e(t)$ and $\dot{Q}_{w0}$. This data is also measured and stored in the TRT test, so it can be used for the present model. Fig. 3 shows how this factor evolves in the initial state of operation.

Fig. 4 shows the results of the measurement of the heat rate, $\dot{Q}_w(t)$, and the electrical power supplied to the resistor, $\dot{W}_e(t)$. The first presents a discrete probability density function, which can be fitted to an analytic normal probability distribution with very few deviations [14]: a mean value of 3988 W and a standard deviation of 2.24% have been observed for heat rate measurements, $\dot{Q}_w(t)$, while the electrical power, $\dot{W}_e(t)$, had a mean of 4000 W and a standard deviation of 0.976%, showing a small difference between the mean values, due to heat absorption by the device. For this last value, it is observed how the electricity consumption in the resistance is established through discrete values, due to the digital character of the control over the solid-state relay that controls the connection time through PWM.

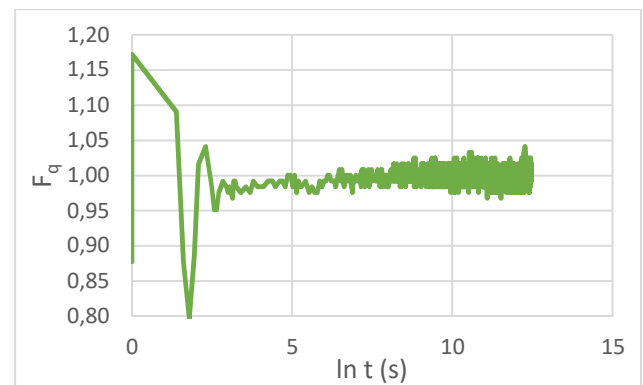


Fig. 3. Load factor as a function of operating time.

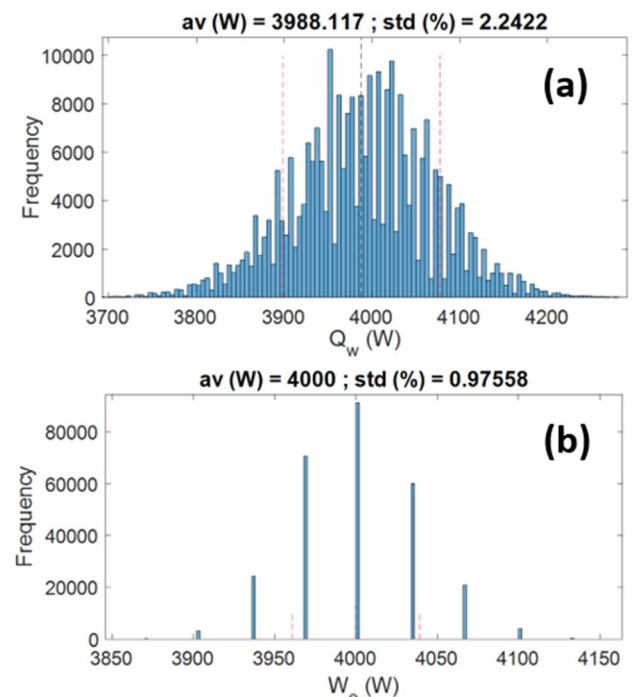


Fig. 4. Histogram for $\dot{Q}_w(t)$, in (a), and for $\dot{W}_e(t)$, in (b).

B. Model of TRT equipment

To simulate the performance of the TRT device, with special interest in the first time steps, a simple model has been built that simulates the heat exchange inside the tank, in which the resistance transfers a heat $\dot{Q}_{w0}$ to it.

Once the temperature of the fluid at the device inlet (GHE outlet) is known, a model can be created to establish its outlet temperature (GHE inlet) at the following step. The variable to be calculated (device outlet temperature) can be validated with experimental data obtained from the TRT test.

This model is based on the application of the First Law of Thermodynamics [15]. In consideration of the adiabatic system, the difference between the heat supplied by the resistance $\dot{W}_e$ and that received by the fluid $\dot{Q}_w$, is stored in the elements of the device, giving rise to the variation of its internal energy dU (including tubes, resistance, and the fluid itself):

$$\dot{W}_e - \dot{Q}_w = \frac{dU}{dt} = C_{eq} \cdot \frac{dT_d}{dt} \quad (1)$$

Where $\dot{Q}_w = \dot{H}_{out} - \dot{H}_{in}$ is the heat flow received by the thermal fluid inside the device, the difference between its enthalpy flow at the outlet, $\dot{H}_{out}$, (GHE inlet) and at the inlet, $\dot{H}_{in}$, (GHE outlet) and the electrical power delivered at each step is the fixed value of the test times its load factor $\dot{W}_e = F_q \cdot \dot{Q}_{w0}$.

In a time interval, Δt , the principle of conservation of energy in a deposit fulfills the expression:

$$\dot{W}_e - \int \dot{H}_{out} dt + \int \dot{H}_{in} dt = \Delta U \quad (2)$$

Using Euler's method, Eq. (2) can be expressed as follows, by approximating dh as $c_p \cdot dt$ in the thermal fluid:

$$\dot{Q}_{w0} \cdot \Delta t \cdot \frac{1}{2} \cdot (F_{q,j} + F_{q,j-1}) - \dot{m} \cdot c_p \cdot \Delta t \cdot \frac{1}{2} \cdot (T_{o,j} + T_{o,j-1}) + \dot{m} \cdot c_p \cdot \Delta t \cdot \frac{1}{2} \cdot (T_{i,j} + T_{i,j-1}) = C_{eq} \cdot (T_{o,j} - T_{o,j-1}) \quad (3)$$

Where C_{eq} (J/K) is the equivalent heat capacity of the set.

The outlet temperature at the later step is the parameter to be calculated. Isolating the corresponding term, the equation is as follows:

$$T_{o,j} \approx [\dot{Q}_{w0} \cdot 0,5 \cdot (F_{q,j} + F_{q,j-1}) \cdot \Delta t + 0,5 \cdot \dot{m} \cdot c_p \cdot (T_{i,j} + T_{i,j-1}) \cdot \Delta t + T_{o,j-1} \cdot (C_{eq} - 0,5 \cdot \dot{m} \cdot c_p \cdot \Delta t)] / (C_{eq} + 0,5 \cdot \dot{m} \cdot c_p \cdot \Delta t) \quad (4)$$

Starting from this expression, a basic model with three tanks (inlet tube without heat input, tank with resistance and outlet tube without heat loss) has been initially analysed, determining C_{eq} in each of them from the geometry and tube materials, fluid and so on. The results are very different from the desirable ones, in no case adjusting the temperature T_o adequately to the experimental data. Using a more

detailed model would greatly increase the complexity of the procedure, slowing down the calculations of the 3D model of the GHE when it is simulated. An alternative solution is to evaluate the simplest possible model, with a single deposit, but with C_{eq} varying over time, constituting an artifice to get an approximation to the real behaviour.

3. Results

As mentioned above, the equivalent heat capacity of the assembly, C_{eq} , is analysed as a time-varying term. This function should follow the trend obtained directly from experimental data. To do this, first the term $C_{eq}(t)$ has been evaluated, clearing it from Eq. (3), introducing as inputs the extreme temperatures of the fluid (inlet and outlet). In Fig. 5, it is observed that it varies with time, oscillating significantly for about 1 hour (blue line). After that period of time, the materials have already stored enough heat and the variation in their temperature is minimal, with slight fluctuations in temperature, so C_{eq} would correspond to a value equivalent to the capacity of all the internal elements (around 105,000 J/K).

From this curve, the variable C_{eq} can be defined as a function composed of n step values within a temporal sequential superposition, where each of those $C_{eq,i}$ originates from a different step ' i ', in the form:

$$C_{eq}(t) = \sum_{i=1}^n (C_{eq,i} - C_{eq,i-1}) \quad (5)$$

This function must follow the trend developed by the one obtained directly from the experimental data. Once this is defined, it is introduced in the model of Eq. (4), and is compared with the experimental curve. Then a procedure is applied, looking for the time values to apply each step ' i ', and its corresponding value of $C_{eq,i}$, so that the simulated response of the fluid outlet temperature of the device is well approximated to the real performance.

Once the search is finished, the following curve shows the optimal function obtained for the $C_{eq}(t)$ model (grey line), next to the previous one. In turn, 12 time steps ' i ' appear with their corresponding $C_{eq,i}$ as shown in Table 1:

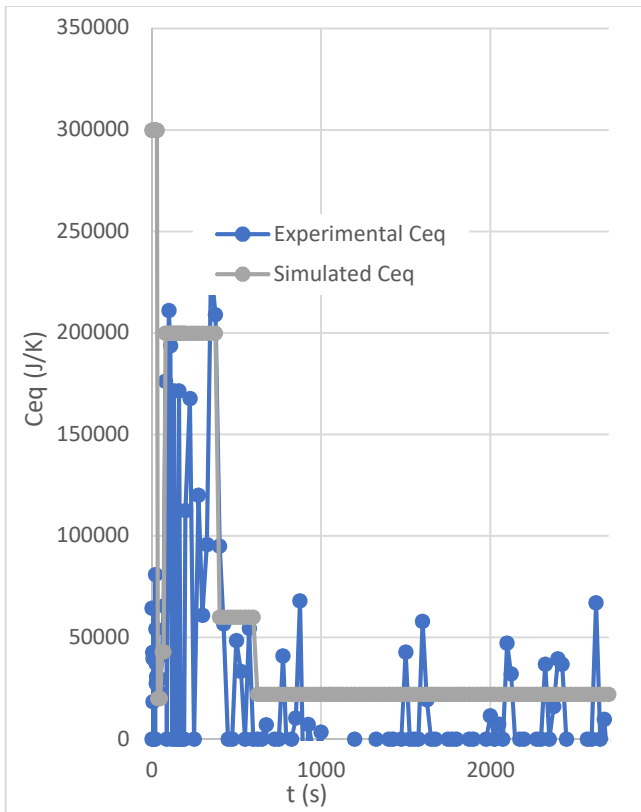


Fig. 5: Evolution of the equivalent heat capacity, $C_{eq,i}$, experimental and simulated

Table 1: Equivalent heat capacity, $C_{eq,i}$, at several time steps

i	t_i (s)	$C_{eq,i}$ (J/K)
1	0	300000
2	32	20000
3	45	20000
4	60	43000
5	80	200000
6	400	60000
7	600	22000
8	1000	22000
9	1500	22000
10	2000	22000
11	2500	22000
12	2900	105000

Using the experimental data from the test in Eq. (4), the outlet temperature of the fluid from the TRT device (inlet to the GHE) has been calculated from its inlet temperature, as well as the load factor (Fig. 6). In Fig. 6 it is observed how the suitable adjustment of the parameters results in an accurate simulation of the outlet temperature when compared with the experimental results, where the maximum error was 0.64 K and the root mean square error (RMSE) was $4.1 \cdot 10^{-4}$ K, so the model has been validated in this way.

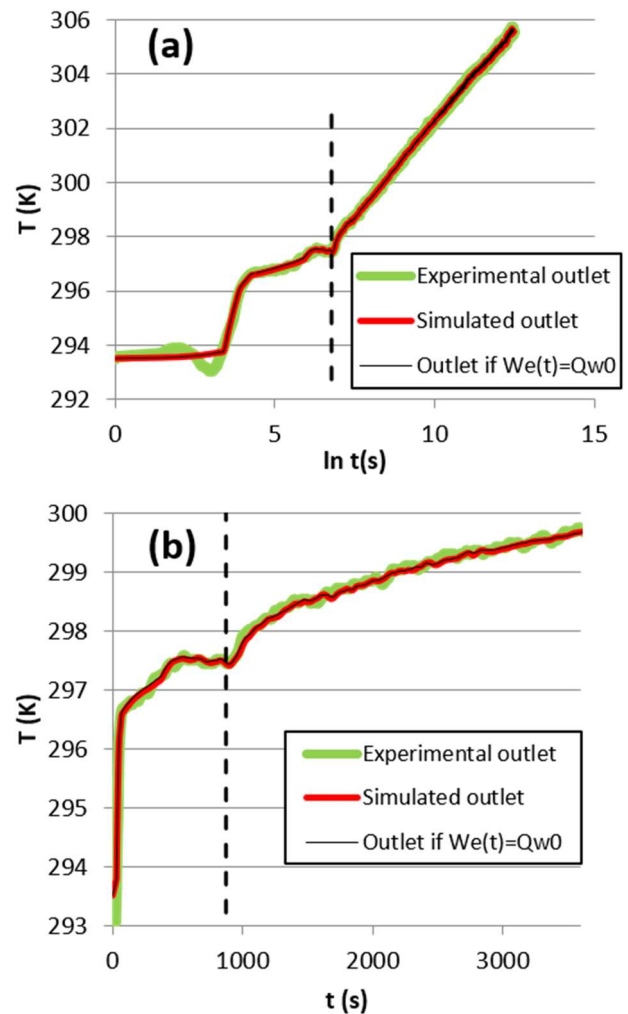


Fig. 6: TRT device outlet temperature in (a) and detail in (b)

The most significant differences occur during the first moments of the test, taking less than one minute. Other phenomena appear here, such as the delay in the heat transfer by the resistor (Joule effect), and non-uniformities in the temperature measurements themselves at the beginning of the test. In this context, after that time, the evolution of the temperature T_i is correct, so that this parameter has been generated synthetically for the entire test in a satisfactory way, thereby validating the defined model.

The use of the load factor has been necessary to validate the behaviour model of the TRT device with experimental data. But when it comes to simulating its performance inside a UDF in 3D simulation software, the actual control effect will not be available. Thus, it is evaluated what happens if, at all times, $\dot{W}_e(t) = \dot{Q}_{w0}$. This performance is also observed in Fig (6), showing that the response will approximately be the same. With this, it can be affirmed that the synthetic test can be carried out without the need to provide functions that control the heat input to the device over time.

4. Conclusions

In this work, a simple model of a device that provides heat to the fluid to carry out TRT tests has been developed. Its main advantages are: i) its simplicity allows it to be included as an auxiliary submodel in the 3D model of the GHE without computational cost. Thus, synthetic data can be generated and the performance of the GHE modeled in other untested conditions, without significantly increasing the calculation time; ii) allows to simulate the behaviour for $F_q = 1$ permanently ($\dot{W}_e(t) = \dot{Q}_{w0}$), removing the need to model the process control; iii) shows the way to develop other simple submodules, such as the external element of a heat pump (condenser in summer and evaporator in winter), which will be integrated into the 3D GHE model.

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