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Borehole modelling: a comparison between a steady-state model and a novel dynamic model in a real ON/OFF GSHP operation

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Abstract. The correct design and optimization of complex energy systems requires the ability to reproduce the dynamic thermal behavior of each system component. In ground source heat pump (GSHP) systems, modelling the borehole heat exchangers (BHE) dynamic response is especially relevant in the development of control strategies for energy optimization purposes. Over the last years, several models have been developed but most of them are based on steady-state approaches, which makes them unsuitable for short-term simulation purposes. In fact, in order to accurately predict the evolution of the fluid temperatures due to the ON/OFF cycles of the heat pump, it is essential to correctly characterize the dynamic response of BHE for very short time periods. The aim of the present paper is to compare the performance of an analytical steady-state model, available in TRNSYS environment (Type 557), with a novel short-term dynamic model. The new dynamic model is based on the thermal-network approach coupled with a vertical discretization of the borehole which takes into account both the advection due to the fluid circulating along the U-tube, and the heat transfer in the borehole and in the ground. These two approaches were compared against experimental data collected from a real GSHP system installed at the Universitat Politècnica de València. The analysis was performed comparing the outlet temperature profiles predicted by both models during daily standard ON/OFF operating conditions, both in heating and cooling mode, and the between both approaches were highlighted. Finally, the obtained results have been discussed focusing on the potential impact that the differences found in the prediction of the temperature evolution could have in design and optimization of GSHP systems.

1. Introduction

Ground source heat pump (GSHP) systems use the ground as a heat source in winter and as a heat sink in summer, taking an advantage of the more stable temperature of the ground, which allows achieving a greater efficiency and, hence, reducing the CO_2 emissions for heating and cooling applications.

Generally, the heat exchange takes place in a ground source heat exchanger (GSHE) and different configurations can be adopted (a detailed review of GSHE systems can be found in [1]). Among those, one of the most commonly used is the vertical borehole field, consisting on



a certain number of borehole heat exchangers (BHE) drilled in the ground, inside which one or more U-tubes are located.

The heat transfer phenomena are complex and occur over a wide spatial and timescales ranges. Therefore, several assumptions are usually made in order to simplify the phenomena, with the aim to realize simplified models which permit to perform fast calculations. In fact, the ability to predict the BHE thermal performance can contribute to find the best solutions to increase the energy efficiency of the whole system.

In the last years, several approaches have been proposed in order to reproduce the thermal behavior of different BHE configurations (a complete review is reported by Yang et al. [2]). The most widely used approach is based on the line and cylindrical heat source theory [3, 4, 5], which models only the heat transfer between the borehole wall and the surrounding soil, neglecting the heat transfer inside the borehole. Eskilson [6] proposed a model based on the use of non-dimensional temperature response factors, called g-functions, that represent the temperature response to a constant heat injection pulse, for a certain time step. Thus, the actual thermal load can be subdivided into a series of constant step loads and then the temperature response can be obtained by superimposing the single response at each load step. This approach is valid only for a time scale greater than 3-6 hours for a typical borehole [7].

The thermal network model represents another simple approach in which the thermo-electrical analogy is adopted to represent the heat transfer phenomena inside the borehole. The basic thermal network is the steady-state delta network [7] in which one temperature node is located on each pipe of the U tube and another one is located on the borehole wall. The thermal network approach can also be used for modelling the behavior of the ground around the borehole, from the undisturbed ground temperature to the borehole wall. Moreover, it is possible to overcome the typical steady-state approach by adding thermal capacitances to each temperature node ([8, 9, 10]), allowing to reproduce the dynamic of the system.

Usually, GSHP systems for heating and cooling in buildings are governed by an ON/OFF control algorithm. In these cases, the thermal load is injected/extracted to the ground in short heat pulses of about 20 minutes approximately (depending on the instantaneous thermal energy demand). In this context, the short-term behavior of BHE represents a crucial topic for evaluating and optimizing the thermal performance of GSHP, especially in terms of system control criteria and heat pump performance (which are strongly affected by the temperature evolution of the working fluid). Therefore, there is a need for software able to reproduce the short term dynamic behavior of the fluid circulation along the BHE. The present paper reports the comparison between two different approaches for modelling a single U-tube for short-term periods:

- the typical DST model provided in Trnsys (Type 557) [11] based on the explicit finite difference method (FDM) coupled with an analytical steady-state solution.
- a novel short-term BHE dynamic model, called Borehole-to-Ground (B2G) model, based on the delta network approach and implemented in the Trnsys environment. This model has been validated against experimental data provided by different system installations in previous authors works.^{1,2}

The analyses have been conducted comparing the BHE outlet temperature profiles obtained by the two different codes with real experimental ones collected during a step-test (7 hours of heat injection) and, moreover, during real ON/OFF operation of the GSHP system installed at the Universitat Politècnica de València,

¹ Ruiz-Calvo, F., De Rosa, M., Acuña, J., Corberán, J.M., Montagud, C. 2014. Experimental validation of a short-term Borehole-to-Ground (B2G) dynamic model. Unpublished results.

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2. Experimental Plant

The experimental data used in the present work were obtained from an operating GSHP system installed at the Universitat Politècnica de València (UPVLC), Spain. The experimental plant was built on 2004 and started its operation on February 2005, in the framework of a European Fifth Framework project called GeoCool [12]. GeoCool plant consists of a reversible water-to-water heat pump, coupled to a ground source heat exchanger (GSHE). The system was designed for air conditioning a total area of approximately 250 m² comprising a set of offices and general purpose rooms.

Figure 1 shows a schematic diagram of the experimental plant, where it can be observed that the system mainly consists of two hydraulic loops coupled by the heat pump. The internal (building) circuit consists of a total of 12 parallel connected fancoils, a circulation pump, and a water storage tank. The external circuit includes the ground source heat exchanger and a circulation pump. The fluid used in both circuits is water. A more detailed description of the installation and the particular conditions of its operation is provided in [13].

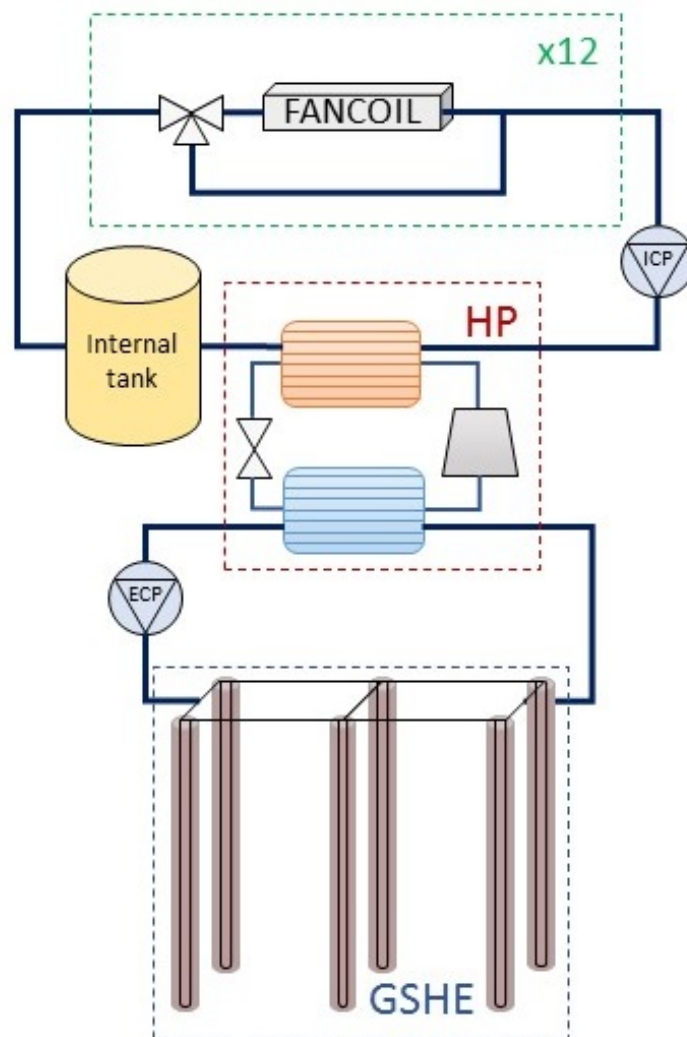


Figure 1. Experimental plant schematic diagram.

The heat pump installed for GeoCool project is a one-step reversible heat pump. The adjustment of the heat pump thermal capacity to the actual thermal load is achieved by an ON/OFF control strategy. This particular mode of operation produces a characteristic temperature evolution along the day, which affects the system performance and the heat pump thermal efficiency. Further improvements on the control algorithm have been implemented recently in order to optimize the overall performance of the plant [14].

The GSHE of the GeoCool plant consists of 6 vertical boreholes, drilled in the ground near the building. The boreholes are arranged in a 2x3 rectangular grid, spaced 3 m from each other, and connected in parallel. Each borehole has a diameter of 150 mm and a depth of 50 m. The water flows throughout the borehole by a U-tube, being the inner and external diameters of 25.4 mm and 32 mm respectively, and a center-to-center distance (shank spacing) of 70 mm. At the top of the U-tube, there are two temperature sensors, which measure the temperature of the water entering and exiting from each BHE. Further details about the design of the GSHE and its characteristics can be found in [15].

3. BHE Models

3.1. B2G Model

A short-term BHE dynamic model, called Borehole-to-Ground (B2G) model, has been developed at Universitat Politècnica de València with the aim of correctly predicting the short-term behavior of U-tube boreholes in terms of water temperature throughout the pipe. The model is based on the thermal network approach considering a discretized domain of the U-tube and the ground in vertical direction. Five thermal capacitances and six thermal resistances are taken into account at each node depth (5C6R-n model, where n is the number of the nodes), considering the thermal properties of the ground, the grout and the pipes and neglecting the vertical heat conduction (Figure 2b).

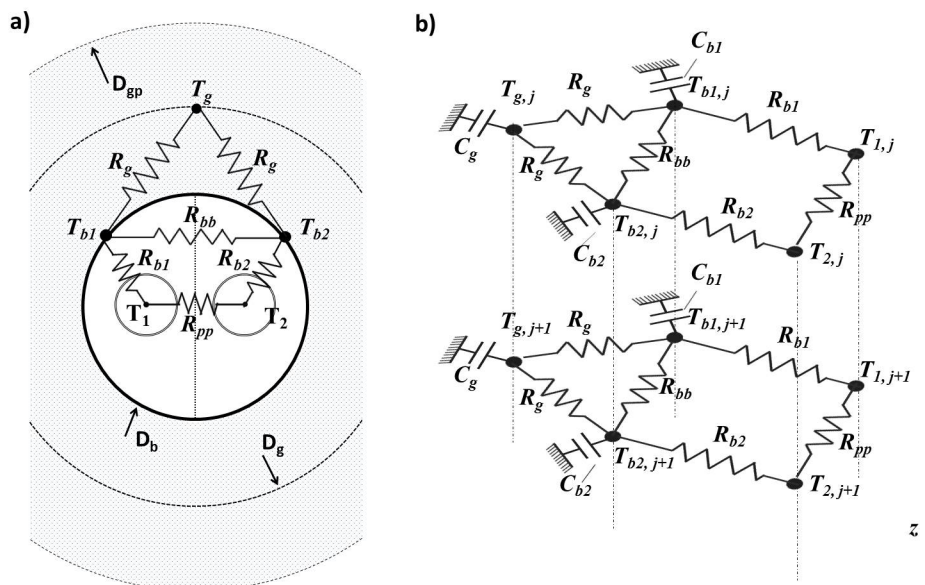


Figure 2. Thermal network model adopted in the present work: a) 2D model; b) 3D model.

The model divides the grout into two separate capacitance nodes according to the pipes location, and it situates the delta network between those nodes and the one located in the surrounding ground. The U-tube is represented by two nodes, one for the downward side and

the other for the upward side. Each fluid node exchanges heat with the correspondent borehole node and with the adjacent fluid node. Moreover, the fluid advection is also taken into account in the energy balance. The balance equations in transient state for all nodes typology correspond to Eqs. 1, 2, and 3.

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

$$C_{b1} \frac{\partial T_{b1}(z)}{\partial t} = \frac{T_1(z) - T_{b1}(z)}{R_{b1}} + \frac{T_{b1}(z) - T_{b2}(z)}{R_{bb}} - \frac{T_{b1}(z) - T_g(z)}{R_g} \quad (2)$$

$$C_g \frac{\partial T_g(z)}{\partial t} = \frac{T_{b1}(z) - T_g(z)}{R_g} + \frac{T_{b2}(z) - T_g(z)}{R_g} \quad (3)$$

The B2G parameters are the thermal resistances and capacitances of the different nodes of the thermal network. These parameters can be determined taking into account the borehole geometrical characteristics and thermophysical properties of each material. In particular:

- the thermal capacitances C_{b1} and C_{b2} are calculated considering the volume of each grout zone;
- the thermal resistance R_{b1} and R_{b2} , supposed to be equal, are calculated starting from the overall borehole thermal resistance, which can be obtained by standard step-test procedures, assuming an equivalent diameter and considering that the borehole nodes have been located at the borehole diameter [10];
- the resistance between the two borehole nodes R_{bb} is obtained assuming a one-dimensional heat transfer, as shown in Eq. 4, in which D_b and $D_{p,e}$ are the borehole and the pipe external diameters, while W is the shank spacing;

$$R_{bb} = \frac{W}{k_b(D_b - D_{p,e})dz} \quad (4)$$

- the thermal resistance between the pipe nodes R_{pp} , which is quite complex to determine due to the two-dimensional heat transfer, is estimated considering a one-dimensional linear heat conduction between them and the convection inside the pipes.
- the ground thermal capacitance C_g is calculated considering the radial penetration depth D_{gp} of the borehole which is an adjustment parameter that depends on the considered heat injection/extraction time and on the ground thermal diffusivity [6]. The ground node is located at D_g , which is calculated as the average between the borehole diameter, D_b , and the penetration diameter, D_{pg} ;
- the thermal resistances R_g between each borehole node and the ground node are calculated considering a cylindrical conductive heat transfer between them.

3.2. TRNSYS Tess Model - Type 557

TRNSYS type 557 implements a vertical BHE model based on the *Duct Ground Heat Storage Model* (DST) developed by Hellström [11]. DST model is focused on the characterization of the temperature profile of the ground around the BHE. The storage region, a cylindrical volume of the ground around the BHE, is discretized using a two-dimensional mesh adopting radial and vertical coordinates. The temperature of each point in the storage region of the ground is calculated with the superposition of a global solution, a steady-flux solution, and a local solution.

The temperature of the outlet fluid of the BHE is calculated by means of a steady-state heat balance, as shown in Eq.5 in which c_f is the heat capacity of the fluid, \dot{m}_f is the flow rate,

$T_f(s, t)$ is the fluid temperature along the pipe, α is the heat transfer coefficient between the fluid and the surrounding ground with temperature T_a .

$$c_f \dot{m}_f \frac{\partial T}{\partial s} + \alpha(T_f - T_a) = 0 \quad (5)$$

Solving this equation by integration along the tube, the outlet BHE fluid temperature can be calculated from Eq.6, in which β is a damping factor defined by equation 7.

$$T_{f,out} = \beta T_{f,in} + (1 - \beta)T_a \quad (6)$$

$$\beta = e^{-\frac{\alpha L}{c_f \dot{m}_f}} \quad (7)$$

As it can be observed in Eq.6 and in Eq.7, the outlet fluid temperature approaches the ground temperature (T_a) when the flow rate tends to zero, while it tends to the inlet temperature ($T_{f,in}$) as the flow rate increases.

Generally, the DST model produces an accurate and detailed prediction of the ground temperature evolution of a BHE. However, it is based on steady-state assumptions, which could affect the performance of the model for very short time steps like the ones existing in ON/OFF GSHP systems for heating and cooling. Moreover, in the prediction of the outlet fluid temperature, advection is not taken into account.

Differences between the results produced by the DST model based on a steady-state approach and the dynamic B2G model are highlighted when confronting both models with experimental data from a real installation operating under ON/OFF conditions. Section 4 presents a comparison of the performance of both models using experimental data from GeoCool Plant.

4. Results

The performance of the B2G model and of the TRNSYS type 557 has been compared, considering experimental data measurements from the GSHP system installed at UPVLC as reference. Both models use as input the inlet water temperature and the water mass flow rate, taken directly from the experimental measurements, and provide the outlet water temperature as an output.

B2G parameters have been estimated using the theoretical approach described in section 3.1. The same parameters have also been used for the TRNSYS model in order to ensure a fair comparison.

The comparison has been conducted comparing the simulated BHE outlet water temperatures provided by B2G and TRNSYS with the experimental measurements. Two different operating conditions were adopted for the comparison. First, the performance of both models has been compared considering experimental data from a step-test in carried out on the 4th of November 2013, in order to validate the transient response of the models. Afterwards, the comparison has been extended to two typical ON/OFF operation conditions for two different days, one in heating and the other in cooling mode. The ability of each model to reproduce the characteristic temperature evolution during ON/OFF cycles has been described and commented.

4.1. Step-test

The step-test was carried out in cooling mode, forcing the heat pump to remain switched on so that the condensing heat was injected into the ground loop during a continuous period of 7 hours approximately. After this time, the heat pump switched off, according to the schedule of the installation, producing a recovery step of 12 hours, also useful for model validation purposes. As previously stated, the input data for both models are the inlet water temperature and the mass flow rate. The simulated outlet water temperature profiles obtained by each approach have been compared against the experimental data. Both inlet and outlet experimental temperatures are measured at the top of the BHE.

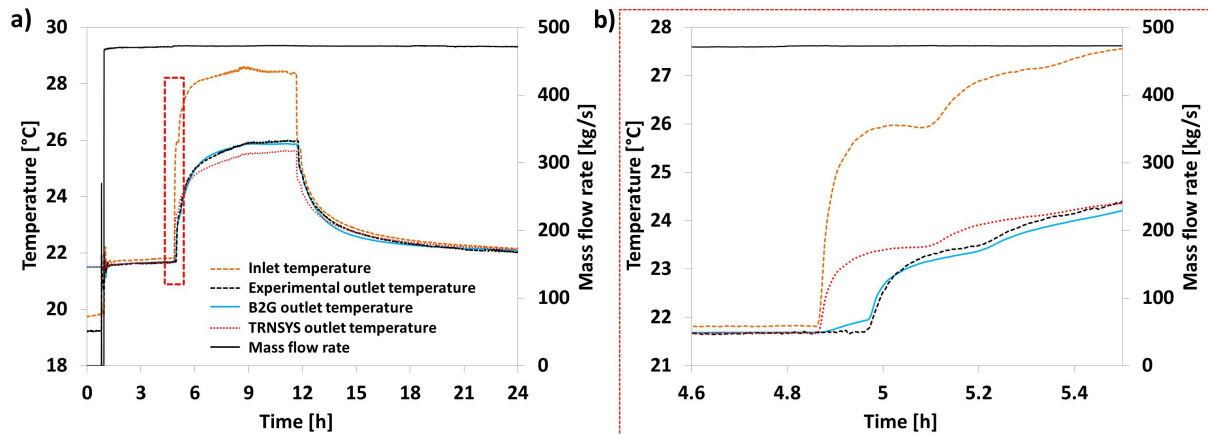


Figure 3. Step-test results: a) general response comparison, b) short-term response comparison (first hours).

Figure 3 shows the comparison results for the step-test simulation. It can be observed that the TRNSYS model predicts an outlet water temperature profile slightly lower than the experimental measurements (Figure 3a), with a difference of around 0.5°C . Although this little discrepancy is perfectly acceptable for simulation purposes, it could be corrected by slightly adjusting the model parameters. On the other hand, B2G results show a very good agreement with the experimental measurements.

Focusing on the short-term temperature evolution shown in figure 3b, it can be observed that the temperature increase at the outlet of the BHE occurs a few minutes after the correspondent increase on the inlet water temperature. This corresponds to the necessary time for the water to travel along the U-tube. B2G response perfectly reproduces this delay, since the advection terms are taken into account in this model. However, TRNSYS model only produces a steady-state response for the outlet water temperature, without taking into account the displacement time of the water inside the pipes. Therefore, the outlet water temperature calculated by the TRNSYS model increases exactly at the same time than the inlet water temperature. In the step-test conditions simulation, this could be easily corrected by adding some kind of delay to the TRNSYS model outlet water temperature, e.g. by means of a loss-less pipe. However, when using this model for a typical day simulation, with ON/OFF cycling, the steady-state approach may introduce non-negligible deviations from reality.

4.2. Typical performance

In order to compare the performance of a typical day, two representative days have been selected, one for heating mode and one for cooling mode.

Figure 4 shows the simulation results for the heating mode operation day (17/02/2010); in particular, Figure 4a presents an overview of the BHE water temperature evolution along the day, while Figure 4b shows an augmented section of the previous one, allowing the detailed study of the temperature evolution along some heat pump cycles.

In order to study the performance of both models, it is necessary to understand the characteristic experimental water temperature evolution that is produced by the ON/OFF cycling of the heat pump. For this purpose, critical points (A-E) have been identified in Figure 4b. First of all, during the OFF periods (from A to B), the evolution of the outlet water temperature depends on the environmental conditions rather than on the BHE performance, since there is no mass flow rate and the water is stopped at the top of the BHE. So, the

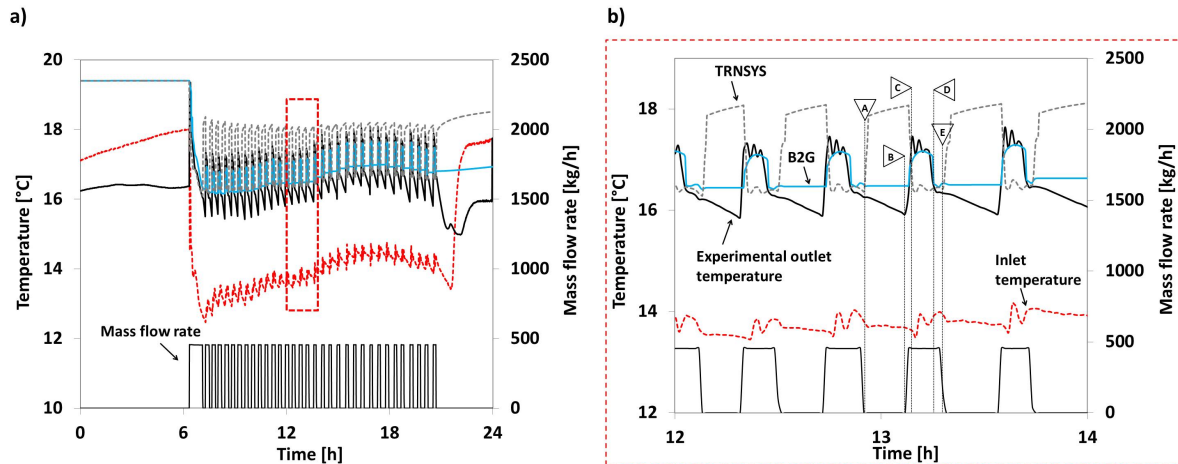


Figure 4. Comparison of both models performance for a typical day in heating mode: a) simulation results for the whole day, b) comparison for two hours of simulation (17/02/2010).

temperature evolution during this period is out of the scope of the studied models and it is not taken into account for the comparison.

On the other hand, at the start of the ON periods (from B to C), there is a sudden increase of the water temperature, due to the displacement of the water that remains inside the borehole during the OFF period, whose temperature tends to the ground one. Water entering the borehole at the start of the ON period takes about 7 minutes to reach the end of the U-tube (point D). At this moment, a temperature decrease can be observed at the outlet water temperature, which remains fairly constant until the heat pump switches off again (point E).

Regarding the response of the studied models, it can be observed that B2G correctly reproduces the outlet water temperature evolution, according to the experimental measurements. All the phenomena described before and related to the water temperature evolution are correctly modelled by the B2G thermal network approach. The differences observed between B2G results and experimental measurements can be attributed to measurements uncertainty and vertical heat transfer effects that are out of the scope of the model.

The TRNSYS model produces a very different output. On one hand, during the OFF periods, since there is no mass flow rate, the calculated outlet water temperature tends to the ground temperature (Eq. 6), which is about 19.4°C . Although this has no further influence on the results of the ON cycle, when integrated in a global model, the BHE model has to be connected to other components which would receive an incorrect water temperature value during the OFF cycle, consequently producing errors in the global model results.

On the other hand, during the ON periods, the temperature evolution is different from the experimental measurements. The values of the temperature match the experimental measurements corresponding to the entering water temperature at the moment it reaches the end of the U-tube (point D), but without taking into account the displacement of the water inside the U-pipe. In this case, delaying the response of the TRNSYS type is not enough to solve the problem: this solution would correct the position of the temperature values but, since the volume of water inside the U-pipe is not taken into account in the TRNSYS model, it would be impossible for this model to correctly reproduce the temperature increasing happening at the start of the ON period (from B to C).

Results for the cooling mode comparison are shown in Figure 5. The results of the simulation and the comparison between the two models with the experimental measurements are analogous

to the ones observed in the heating mode comparison.

The differences observed in the response of both models may not be highly relevant from a long-time evolution point of view. However, instantaneous water temperatures are directly related to the heat pump efficiency and capacity. Moreover, control algorithms that might be used in the installation usually act according to the instantaneous temperature measurements. Therefore, for a short-term analysis of the system, it will be necessary to use a model capable of reproducing the instantaneous temperature response. Results presented in this section have shown that TRNSYS model would not be useful for this purpose. On the contrary, B2G produces an accurate enough prediction of the BHE outlet water temperature and it is useful for short-term simulations.

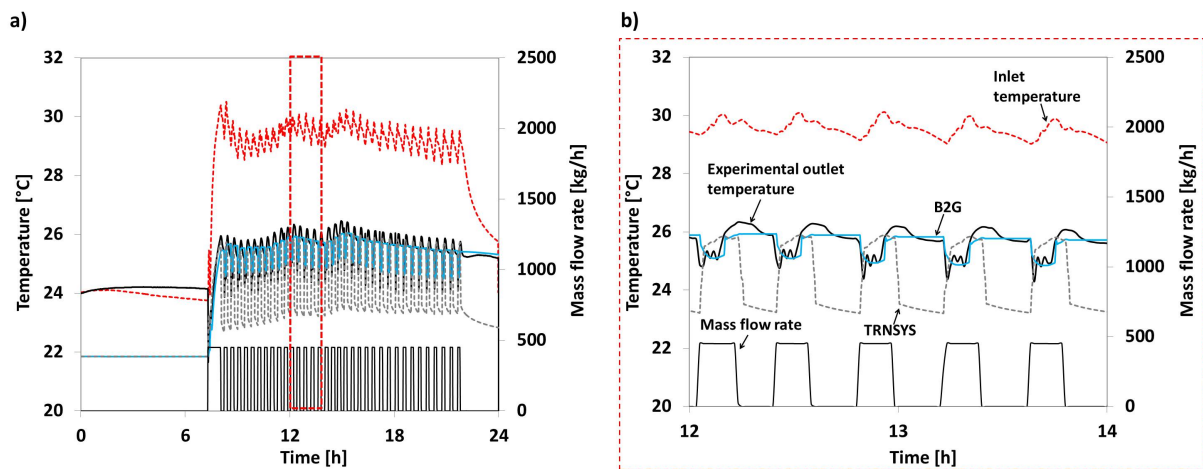


Figure 5. Comparison of both models performance for a typical day in heating mode (17/09/2010).

5. Conclusions

The aim of this work was to compare the performance of two different BHE models, regarding their ability to predict the outlet water temperature of the borehole. A novel BHE model called B2G was presented. This model is based on a dynamic approach using a thermal network, and has been validated in previous works. B2G model was compared to the one already existing in the TRNSYS software (type 557), based on a steady-state approach. For the comparison, experimental data from a real installation located at UPVLC was used.

Two different operating conditions were simulated: (i) a step-test and (ii) typical operating conditions of a GSHP installation for heating and cooling mode. The response of both models for the step-test simulation was very similar. However, it was found that the TRNSYS model could not reproduce the temperature delay corresponding to the time that the water takes to circulate through the U-tube of the borehole. On the other hand, in (ii), real operating conditions were simulated, which included several ON/OFF cycles. In this case, B2G proved to be able to reproduce the water temperature evolution with a great accuracy, while the TRNSYS model wasn't able to provide a satisfactory result, due to the steady-state approach on which it is based.

The differences observed between both models predictions highlight the importance of using a detailed dynamic approach when modeling a BHE, especially at ON/OFF operating conditions. In fact, assuming a steady-state approach could lead to inaccurate outlet water temperature

predictions, which may introduce errors in calculating the heat pump efficiency or in the application of temperature control algorithms.

Acknowledgments

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