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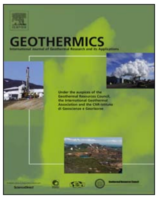

Sensitivity analysis of a vertical geothermal heat exchanger dynamic simulation: Calibration and error determination

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ABSTRACT

This paper implements a sensitivity analysis of a vertical Geothermal Heat Exchanger model from a Ground Coupled Heat Pump system, simulated with the software TRNSYS. Afterward, the optimization software GenOpt is applied in an iterative calibration process, calibrating those factors that were proven to be the most important in the sensitivity analyses. A comparison is made between the calibrated simulation and the experimental data collected from the system, obtaining a significant reduction in the error. The results demonstrate that the methodology used is effective, which indicates that a sensitivity analysis is an appropriate method to determine which parameters should be calibrated, while avoiding biases of the modeler and decreasing the number of iterations required in the calibration by approximately 89%.

1. Introduction

In recent years, decreasing the demand for energy and reducing environmental impacts of the energy sector have become two major concerns for the European Union. Buildings represent more than the 40% of the total energy consumption in the European Union (DIRECTIVE, 2010). Moreover, buildings are vital to accomplishing the target of decreasing Greenhouse Gas Emissions by reducing energy demand from fossil fuels and enhancing energy efficiency in facilities (DIRECTIVE, 2012). Therefore, the use of renewable energy, such as geothermal energy, in residential and commercial buildings will help to achieve these challenging objectives. In this context, geothermal exploitation at very low temperatures using a Ground Source Heat Pump (GSHP) system is posited as an ideal solution to meet the requirements for heating and cooling different types of buildings and can encompass a wide range of energy demand from small residences to large commercial and institutional buildings (Atam and Helsen, 2016; Sarbu and Sebarchievici, 2014; Saner et al., 2010; Bayer et al., 2012).

One of the main advantages of the GSHP system is the high energy efficiency compared to other conventional air conditioning systems (Atam and Helsen, 2016; Sarbu and Sebarchievici, 2014; Mustafa Omer, 2008; Urchueguía et al., 2008), reaching Coefficients Of Performance (COP) of 3–5 (Sarbu and Sebarchievici, 2014; Desideri et al., 2011). The most applied GSHP technology is the Ground Coupled Heat Pump (GCHP). The three main components of a GCHP are the Geothermal Heat Exchanger (GHE), the heat pump unit coupled with the ground connection, and the heat distribution system (Sarbu and Sebarchievici, 2014; Sebarchievici and Sarbu, 2015). The most common configuration of the GHE is the vertical layout. The vertical GCHP system requires a smaller soil area for the closed-loop connection, drawing more thermal energy per unit of length (Sarbu and Sebarchievici, 2014). However, installation costs for a vertical GCHP are typically higher because of the expensive equipment necessary for drilling the boreholes (Sarbu and Sebarchievici, 2014; Han and Yu, 2016).

Recently, GHE systems have been the subject of numerous studies due to the importance of these systems as a source of renewable energy and their increasing use worldwide (Soni et al., 2015). Li and Lai (2015) provide a comprehensive review of the analytical models of GHE systems, evaluating several models in a time and space framework. Additionally, Kim et al. (2016) used experiments and numerical analyses to assess the behaviour of horizontal ground heat exchangers. D'Arpa et al. (2016) compared both configurations of the GHE (vertical and horizontal) with conventional fossil-fuel heating systems and concluded that this system can satisfy the heating energy demands with reasonable payback periods. Liang et al. (2014) developed a conformal mapping method to study the thermal properties of U-shaped borehole heat-exchangers and the influence of the parameters on the outlet temperature. They compared the results of four cases of experimental data, achieving a high level of accuracy with the method. For those cases when the periods of heat extraction and injection from the ground are not balanced, Yu et al. (2016) have proposed a zoning operation strategy to lighten the thermal accumulation. This method has proven to be more effective when the thermal conductivity of the ground is small. In the field of improving GHE performance, Qi et al. (2016) studied the use of

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phase change materials (PCM), instead of the usual materials, as backfill in the boreholes.

The design of a GSHP system is generally based on predictions obtained from simulation tools (Soni et al., 2015; Magraner et al., 2010; Nagano et al., 2006). Moreover, the optimal design of the GHE is complex and depends on many factors. Therefore, in this context, the simulation becomes really useful. Dynamic simulation tools have the advantage of enabling the assessment of system operations, the study of energy efficiency and the implementation of improvements to optimize the model (Arteconi et al., 2013). Several authors have applied dynamic simulations to GSHP systems and compared them to experimental data (Desideri et al., 2011; Sebarchievici and Sarbu, 2015; Magraner et al., 2010; Arteconi et al., 2013; Chargui et al., 2012; Montagud et al., 2013; Rad et al., 2013). These authors have worked with the software simulation tool TRNSYS. Desideri et al. (2011) evaluated the efficiency of a GSHP from a residential building by calculating the COP in warm and cool seasons. Additionally, Rad et al. (2013) have studied the viability of hybrid GSHP systems using solar thermal collectors as supplements in heating modelling with TRNSYS. Therefore, TRNSYS, as a software simulation tool, has been widely used and has been proven to provide reliable results.

To adjust the results achieved by simulating the model to those produced in the actual installation, a calibration of the simulation is performed. ASHRAE Guideline 14 (R.a.A.-C.E. American Society of Heating, INC., 2002) states that a whole building can be considered calibrated when the computer model has a Normalized Mean Bias Error (NMBE) of 5% and a Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) of 15% relative to the monthly calibration data. If the data sampling period is hourly, these requirements are 10% and 30%. These requirements could be extended to each part of the building as the thermal energy source. A common problem encountered in calibration is the high number of parameters that need to be varied. This implies that the number of iterations required to achieve optimal results increases significantly and that the utilized algorithm finds mathematical minima, which are not consistent with the physical reality of the model. Moreover, the experts who perform the optimization tend to introduce their own bias in the calibration model. Hence, it is helpful to know beforehand how the model behaves to determine which variables have a greater effect on the outputs of the simulation, thus reducing the number of variables used in the calibration.

A sensitivity analysis (SA) seeks to characterize the reaction of the output to changes in the inputs. It is a useful tool to detect the main factors affecting the model performance and determine the factors that are less relevant and, thus, can be discarded in subsequent calibration. Several authors have conducted studies on this topic. Rad et al. (2013) conducted an SA of unknown ground thermal conductivity to study its effects on fluid temperature. Magraner et al. (2010) performed an SA of energy performance simulation results and concluded that the heat pump nominal COP was the parameter that most significantly affects energy performance predictions. Li et al. (2016) performed an analysis to investigate how the parameters of an Enhanced Geothermal System relate to optimize the system by calculating the optimal flow rate that maximizes the value of incomes for a number of different borehole configurations. Arteconi et al. (2013) completed an SA for GCHP design parameters, quantifying the sensitivity by means of the Pearson correlation coefficient and concluding that the tank temperature set point in winter was the parameter with the greatest influence over energy consumption. Other authors found that the groundwater flow was the most important factor in thermal recovery (Dehkordi and Schincariol, 2014).

In the present work, a detailed study of a GHE simulation is performed. First, a vertical GHE is modelled and simulated using the software TRNSYS, and the simulation results are compared with actual data. An SA, implemented through three different methodologies, is performed to discover which factors are most important and how they affect the results. Subsequently, these factors are considered to perform a more efficient calibration using the optimization software tool GenOpt. Finally, the calibrated simulation is validated by comparing it with data from the existing GCHP system, achieving a transient simulation of the facility with a significant reduction in the committed error.

2. Description of the experimental system

The GHE model simulated is contrasted to the actual installation of the experimental system. Data are collected during the period from the 1st of January of 2016 to the 23rd of May of 2016 for a building heated by a vertical GCHP system and an underground heating system. The thermal energy production system and the GHE were monitored during this period corresponding to the heating mode of the pump.

The building under consideration is the public library of the Faculty of Marine Sciences at the University of Vigo, which is located in Northwest Spain. This building has been analysed and simulated in detail by Cacabelos et al. (2015) This study focused on the portion of the energy generation system corresponding to the geothermal borehole installation. Therefore, the characteristics of these boreholes are described here.

2.1. *Geothermal field description*

The GHE system consisted of six boreholes distributed in two rows with three wells per row. The boreholes are 100 m deep and filled with bentonite. Each borehole has a diameter of 140 mm and contains two polyethylene U double tubes (four tubes) with a nominal diameter of 32 mm. The distance between the boreholes is 5 m, and they are connected in parallel.

The carrier fluid that circulated inside the pipes is a mixture of water and 20% ethylene glycol. According to the design features of the GHE, in the heating mode, the temperature of the carrier fluid is 7 °C at the inlet of the borehole and 12 °C at the exit.

The characteristics of the GHE used in this study are those defined in the project. The characteristics are provided in Table 1 along with the values used in the SA and calibrations that will be further explained. A graphical clarification of the parameters that define the geometry of the borehole can be seen in Fig. 4.

Fig. 1 shows the supply and return collectors of the boreholes along

Table 1
Definition parameters of the GHE model and the limit values for the SA and calibration.

Name of the parameter	ID	Design Value	Units	Inf. Limit	Sup. Limit
Borehole Depth	x1	100	m	90	110
Header Depth	x2	0.200	m	0.100	2.000
Borehole Radius	x3	0.070	m	0.050	0.090
Storage Thermal Conductivity	x4	2.920	W/m K	1.390	5.560
Storage Heat Capacity	x5	2400	kJ/m^3 K	1000	4000
Outer Radius	x6	0.016	m	0.015	0.018
Inner Radius	x7	0.013	m	0.011	0.014
Center To Center Distance	x8	0.029	m	0.020	0.040
Fill Thermal Conductivity	x9	0.940	W/m K	0.140	1.390
Pipe Thermal Conductivity	x10	0.420	W/m K	0.140	1.390
Gap Thermal Conductivity	x11	1.400	W/m K	0.280	5.560
Gap Thickness	x12	0.000	m	0.000	0.100
Borehole Flow	x13	917	kg/h	300	1700
Reference Fluid Temperature	x14	7	°C	5	35
Fluid Specific Heat	x15	3.795	kJ/kg K	2.000	6.000
Fluid Density	x16	1052	kg/m^3	900	1200
Fluid Max Temperature	x17	100	°C	80	120
Initial Storage Temperature	x18	14.470	°C	12.000	18.000
Flow	x19	5500	kg/h	2000	10000
Borehole Spacing	x20	5.000	m	4.000	6.000