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Comparison Between Simulation and Experimental Results for a Monitored Ground Coupled Heat Pump System

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ABSTRACT

The use of computer models for performance predictions has become a standard procedure for the design and management of geothermal heat pump systems. Simulation tools efficacy is dependent not only on the accuracy of their calculations but on the skills of choosing appropriate models and input values. This work compares a ground coupled heat pump design methodology with experimental results. We calculate the system energy performance factor of a monitored geothermal heat pump system analyzing the instantaneous measurements of temperature, flow and power consumption and we compare the performance factor at the end of each season (seasonal performance factor) with simulation results. This simulation is performed with the TRNSYS software tool. We obtain that the simulation results for the seasonal energy performance factor are compatible with the experimental values.

1. INTRODUCTION

Ground coupled heat pumps are recognized by the U.S. Environmental Protection Agency as being among the most efficient and comfortable heating and cooling systems available today. These pumps represent a good alternative as system for heating and cooling buildings (see references Urchueguía et al (2006), Urchueguía et al (2008), Omer (2008), Lund and Freeston (2000), Lund (2001), Florides and Kalogirou (2007), Sanner et al (2003), Spitler (2005)). By comparison with standard technologies, these pumps offer competitive levels of comfort, reduced noise levels, lower greenhouse gas emissions and reasonable environmental safety. Their electrical consumption and maintenance requirements are lower than those required by conventional systems and, therefore, have lower annual operating cost (see Lund (2000), Catan and Baxter (1985), Martin (1990)).

The design of a ground coupled heat pump HVAC (Heating, Ventilation and Air Conditioning) system is based on predictions coming from simulation tools. First step in a standard design procedure is the estimation of the thermal loads that the air-conditioned area is going to demand. Its value determines the capacity of the ground source air-conditioning system. From this value and a proper estimation of the ground thermal properties, it is given a choice for the characteristics of the water to water heat pump and for the length and layout of the borehole heat exchangers.

The purpose of this work is to compare a standard design procedure based on a TRNSYS (see Klein et al (2004)) simulation with the experimental results obtained on a monitored geothermal plant. There are research works focused in the experimental validation of design models for thermal facilities (see Chowdhury et al (2009), Zhou et al (2008)), and also others dealing with the experimental validation of modules developed for the TRNSYS software tool (see Mondol et al (2007), Ahmad et al (2006)). Nevertheless, there are few references dealing about the experimental validation of models for ground coupled heat pumps working in heating and cooling mode. In Europe, research in this area has been performed in Turkey, with the objective of experimentally characterize the system performance, and also in the development of models to predict this performance. On the experimental characterization of ground coupled heat pump system performance working in both operation modes, heating and cooling, we mention the studies of Hepbasli (2002) and Inalli and Esen (2005). There are also studies of ground coupled heat pump system performance when combined with thermal solar energy (see Ozgener and Hepbasli (2005)). On the development of models to predict ground coupled heat pump system performance we mention the studies by Esen et al (2008). These authors have also developed research in the subject of the present work. In Esen et al (2007) it is presented experimental data for a heat pump coupled to a horizontal ground heat exchanger. These experimental measures are used to validate a finite differences numerical model describing ground heat transfer. In Hepbasli and Tolga (2007) experimental data for a ground coupled heat pump system are used to evaluate the energy system performance. Finally we mention the recent research developed in China on the subject of ground coupled heat pumps working in refrigeration mode (see Fan et al (2008), Yu et al (2008), Li et al (2006), Gao et al (2008)).

One of the difficulties that appear when comparing experimental data with predictions coming from simulation tools comes from the fact that the actual thermal loads differ significantly from the estimated ones. In this work we use the measured thermal loads as input value of the simulation design tool to evaluate the goodness of the models describing the ground coupled heat pump HVAC system. What we present in this study is the comparison between the energy performance measured in GeoCool geothermal experimental plant and the predictions coming from a TRNSYS simulation, using as input values the thermal loads measured along a whole year of measurements.

This article is structured as follows. In Section 2 we describe the experimental setup of GeoCool installation and the analysis procedure for the data. Afterwards, in Section 3, we explain the simulated system, its structure, inputs and outputs. In Section 4 we present and discuss the results, comparing simulation outputs with experimental data. Finally, in section 5 we summarize the conclusions obtained from the presented results.

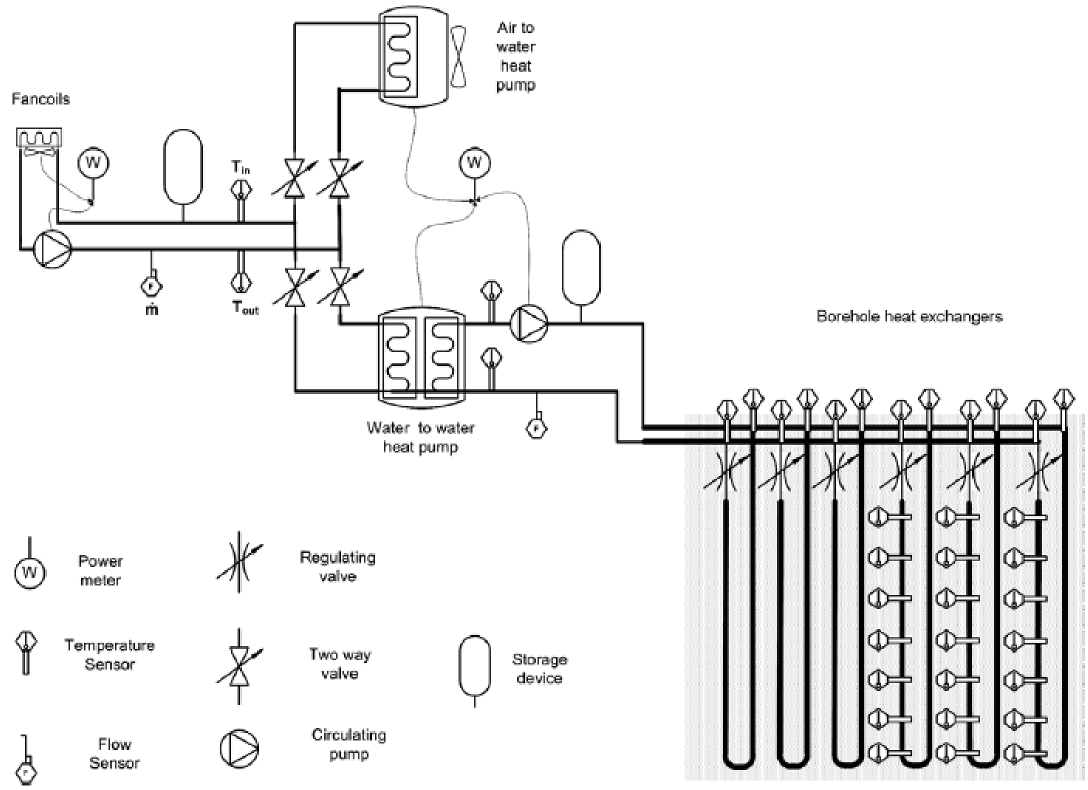

Figure 1: GeoCool schematic diagram. The air to water heat pump and the ground coupled heat pump are working alternately to transfer the energy to fan coils. It shows the location of all measurement sensors

2. GEOTHERMAL EXPERIMENTAL PLANT

Geothermal experimental system, GeoCool plant, air-conditions a set of spaces in the Departamento de Termodinámica Aplicada at the Universidad Politécnica de Valencia, Spain, with a total surface of approximately 250 m^2. This area includes nine offices, a computer classroom, an auxiliary room and a corridor. All rooms, except the corridor, are equipped with fan coils supplied by the experimental system: an air to water heat pump and a ground coupled (geothermal) heat pump working alternately (see Figure 1). The geothermal system consists of a reversible water to water heat pump (15.9 kW of nominal cooling capacity and 19.3 kW of nominal heating capacity), a vertical borehole heat exchanger and a hydraulic group. The water to water heat pump is a commercial unit (IZE-70 model manufactured by CIATESA) optimized using propane as refrigerant. As reported in GeoCool final publishable report (see reference GeoCool (2006)) the coefficient of performance of the improved heat pump is 34% higher in cooling and 15% higher in heating operation.The vertical heat exchanger is made up of 6 boreholes of 50 m. depth in a rectangular configuration (2x3). All boreholes are filled with sand and finished with a bentonite layer at the top to avoid intrusion of pollutants in the aquifers. In the following paragraphs we describe GeoCool data acquisition system and the procedure to evaluate the energy performance of the system.

2.1 Data acquisition System

GeoCool plant was designed to make a comparison between a ground source (geothermal) heat pump system and an air source heat pump system (see references Urchueguía et al (2006), Urchueguía et al (2008)), therefore a network of sensors was set up to allow monitoring the most relevant parameters of these systems (see Figure 1). These sensors measure temperature, mass flow and power consumption. The temperature sensors are four wire PT100 with accuracy ±0.1 ºC. The mass flow meters are Danfoss Coriolli meters, model massflo MASS 6000 with signal converter Compact IP 67 and accuracy <0.1%. The power meters are multifunctional power meters from Gossen Metrawatt, model A2000 with accuracy ±0.5% of the nominal value. Data from this sensor network is collected by a data acquisition unit Agilent HP34970A with plug-in modules HP34901A.

The geothermal system is characterized by the heat that ground can absorb or transfer. To obtain this value inlet and outlet fluid temperature of the water to water heat pump and circulating mass flow are recorded. In addition inlet and outlet temperature in each borehole are measured too and in three of the boreholes the temperature at several depths is recorded to acquire ground temperatures.

2.2 System Energy Efficiency

To calculate the geothermal system energy efficiency is necessary to measure the power consumption and the parameters that characterize internal thermal loads. As we can see in Figure 1 there is a power meter located on the right which has two functions: record the consumption of the air to water heat pump including the fan when the air system is working or record the consumption of the water to water heat pump plus the circulation pump when the geothermal system is working. Thermal capacity ($\dot{Q}$) is calculated measuring the values T_{in} (temperature of the water entering the fan-coil system), T_{out} (temperature of the water leaving the fan-coil system) and $\dot{m}$ (mass flow in the internal hydraulic group) showed in Figure 1 with temperature sensors and a Coriolis meter. Using these values, we obtain the thermal capacity by means of the following expression:

$$\dot{Q}(t) = \dot{h}_{out}(t) - \dot{h}_{in}(t) = \dot{m}Cp\left[T_{out}(t) - T_{in}(t)\right] \quad (1)$$

Cp is the fluid specific heat. This function represents the difference between the output ($\dot{h}_{out}$) and input ($\dot{h}_{in}$) enthalpy flow at the circuit connecting the fan coils and the heat pump. Because of all the measures are taken in one minute intervals, the internal thermal load (Q) is defined as the integral of expression (1). It represents the cooling or heating load demanded by the building during the time period Δt starting at T_0 time.

$$Q = \int_{T_0}^{T_0+\Delta t} \dot{Q}(t)dt \quad (2)$$

Likewise, the system energy consumption (W) is calculated by integrating numerically the recorded power consumption (water to water heat pump, $\dot{W}_{ww}$, and circulation pump, $\dot{W}_{cp}$).

$$W = \int_{T_0}^{T_0+\Delta t} \left(\dot{W}_{ww}(t) + \dot{W}_{cp}(t)\right)dt \quad (3)$$

The energy performance factor is defined as the ratio between the thermal load and the electric consumption during a time interval.

$$PF = \frac{Q}{W} \quad (4)$$

Depending on the duration of the integration period the performance factor can be seasonal, monthly, daily, etc. The most representative one is the seasonal performance factor (SPF) that estimates the system performance in a working mode (heating or cooling).

3. SIMULATED SYSTEM

The aim of this work is to compare a ground coupled heat pump design methodology with experimental results; therefore we study and simulate GeoCool plant with TRNSYS software tool, used usually by geothermal engineers.

TRNSYS (see Klein et al (2004)) is a transient system simulation program with a modular structure that was designed to solve complex energy system problems by breaking the problem down into a series of smaller components (referred to as “Types”). TRNSYS Library includes the components commonly found in a geothermal system (ground heat exchanger, heat pump, circulation pump, etc) and the program allows to directly join the components implemented using other software (e.g. Matlab or Excel). In this case, this feature is important because the simulation uses as input values the experimental thermal loads measured in GeoCool experimental plant, stored in an Excel file.

Figure 2 shows TRNSYS model used to simulate GeoCool plant. The model consists of four components (loads, water to water heat pump, circulation pump and vertical ground heat exchanger). Excel type called Loads contains the experimental thermal loads which are the inputs for the simulation; the other components have been selected from TRNSYS library and they are described next.

3.1 Water to Water Heat Pump (WWHP)

The water to water heat pump selected component is a reversible heat pump; it supplies the thermal loads absorbing energy from (heating mode) or rejecting energy to (cooling mode) the ground. This type is based on user-supplied data files containing catalogue data for the capacity and power draw, based on the entering load and source temperatures. We have modified these files (one for heating and one for cooling) introducing the values of the GeoCool commercial unit (CIATESA IZE-70). We have also included the performance improvement coming from using propane as refrigerant instead of R-407c (an increment of 34% for the Efficiency Energy Rate, EER, and an increment of 15% for the coefficient of performance, COP, as reported in GeoCool final report (see reference GeoCool (2006)). These corrections have been included by diminishing the value of the absorbed power by the compressor for the same amount of generated thermal power. The model is able to interpolate data within the range of input values specified in the data files but it isn’t able to extrapolate beyond the data range.

The component works with two control signals: heating and cooling. When one of these signals are on, the model calls the corresponding data file and calculates the coefficient of performance (COP), the energy absorbed ($\dot{Q}_{absorbed}$) or rejected ($\dot{Q}_{rejected}$)and the outlet temperatures of the water in the internal (load) and external (source) circuits. In our case source means ground heat exchanger. These values are given by the following equations.

In heating mode:

$$COP = \frac{\dot{Q}_{ww,heating}}{\dot{W}_{ww,heating}} \quad (5)$$

$$\dot{Q}_{absorbed} = \dot{Q}_{ww,heating} - \dot{W}_{ww,heating} \quad (6)$$

$$T_{source,out} = T_{source,in} - \frac{\dot{Q}_{absorbed}}{\dot{m}_{source}\, Cp_{source}} \quad (7)$$

$$T_{load,out} = T_{load,in} - \frac{\dot{Q}_{ww,heating}}{\dot{m}_{load}\, Cp_{load}} \quad (8)$$

Being $\dot{Q}_{ww,heating}$ the heat pump capacity at current conditions, $\dot{W}_{ww,heating}$ the heat pump power consumption, $T_{source,in}$ the temperature of the water entering the external (source) system, $T_{source,out}$ the temperature of the water leaving the external (source) system, $T_{load,in}$ the temperature of the water entering the internal (load or fan-coil) system, $T_{load,out}$ the temperature of the water leaving the internal (load or fan-coil) system, $\dot{m}_{source}$ the mass flow in the external circuit, $\dot{m}_{load}$ the mass flow in the internal circuit, Cp_{source} is the specific heat of the fluid in the external circuit and Cp_{load} is the specific heat of the fluid in the internal circuit.

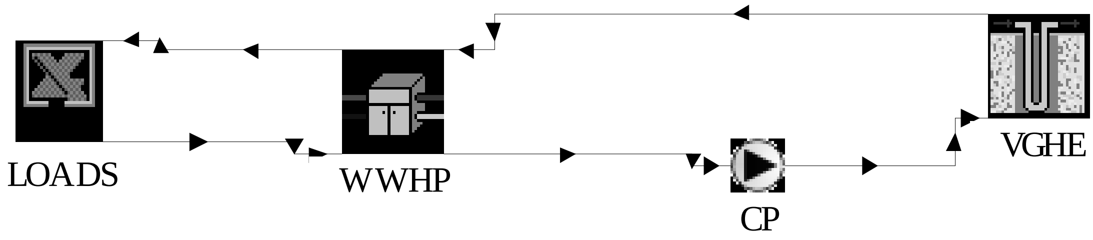

Figure 2: TRNSYS model used to simulate GeoCool plant. LOADS means the excel file storing the hourly thermal loads experimentally measured, WWHP means TRNSYS model describing the water to water heat pump, CP means TRNSYS model describing the circulation pump and VGHE means TRNSYS model describing the vertical ground heat exchanger

In cooling mode:

$$COP = \frac{\dot{Q}_{ww,cooling}}{\dot{W}_{ww,cooling}} \quad (9)$$

$$\dot{Q}_{rejected} = \dot{Q}_{ww,cooling} + \dot{W}_{ww,cooling} \quad (10)$$

$$T_{source,out} = T_{source,in} + \frac{\dot{Q}_{rejected}}{\dot{m}_{source}\, Cp_{source}} \quad (11)$$

$$T_{load,out} = T_{load,in} + \frac{\dot{Q}_{ww,cooling}}{\dot{m}_{load}\, Cp_{load}} \quad (12)$$

Being $\dot{Q}_{ww,cooling}$ the heat pump capacity at current conditions, $\dot{W}_{ww,cooling}$ the heat pump power consumption, $T_{source,in}$ the temperature of the water entering the external (source) system, $T_{source,out}$ the temperature of the water leaving the external (source) system, $T_{load,in}$ the temperature of the water entering the internal (load or fan-coil) system, $T_{load,out}$ the temperature of the water leaving the internal (load or fan-coil) system, $\dot{m}_{source}$ the mass flow in the external circuit, $\dot{m}_{load}$ the mass flow in the internal circuit, Cp_{source} is the specific heat of the fluid in the external circuit and Cp_{load} is the specific heat of the fluid in the internal circuit.

3.2 Circulation Pump (CP)

The circulation pump component is a simple speed model which computes a mass flow rate using a variable control function, which must have a value between 1 and 0 (*f*). The user can fix the maximum flow capacity, in our model established by the heat pump, and the pump power is calculated as a linear function of mass flow rate, defined in the following expression:

$$W_{cp} = W_{\max,\ cp} \frac{\dot{m}_{source}}{\dot{m}_{\max,\ source}} = W_{\max,\ cp}\ f \quad (13)$$

$W_{\max,\ cp}$ and $\dot{m}_{\max,\ source}$ are the pump power consumption and the water mass flow when the pump is operating at full capacity and $\dot{m}_{source}$ is the water mass flow through the pump in each time step, obtained by multiplying the maximum flow rate by the control signal.

3.3 Vertical Ground Heat Exchanger (VGHE)

A vertical ground heat exchanger model must analyze the thermal interaction between the duct system and the ground, including the local thermal process around a pipe and the global thermal process through the storage and the surrounding ground. GeoCool ground heat exchanger has been modelled using ‘Duct Ground Heat Storage Model’ (see Hellström (1989)). This model assumes that the boreholes are placed uniformly within a cylindrical storage volume of ground. There is convective heat transfer within the pipes, and conductive heat transfer to the storage volume. The temperature in the ground is calculated from three parts; a global temperature, a local solution, and a steady-flux solution. The global and local problems are solved with the use of an explicit finite difference method. The steady flux solution is obtained analytically. The temperature is then calculated using superposition methods.

The user can define ground thermal properties as thermal conductivity and heat capacity and also determine the main heat exchanger characteristics (depth, radius, number of boreholes, etc.). In table 1 we show the parameters used in the simulation.

In order to evaluate the ground thermal properties at GeoCool site, laboratory experiments on soil samples were performed. The fill thermal conductivity considered is the average value for wet sand. Also U-tube pipe parameters are the properties of polyethylene pipes DN 32 mm PE 100.

Table 1. Description Parameters of the Ground and of the Borehole Heat Exchanger (BHE).

BHE parameters	**Value**
Number of boreholes	6
Borehole depth	50 m
Borehole radius	0.120 m
Outer radius of u-tube pipe	0.016 m
Inner radius of u-tube pipe	0.0131 m
Center to center half distance	0.035 m
Fill thermal conductivity	2.0 W/m K
Pipe thermal conductivity	0.42 W/m K
Ground parameters	**Value**
Undisturbed ground temperature	18.0 ºC
Storage thermal conductivity	1.43 W/m K
Storage Heat Capacity	2400 kJ/m^3/K

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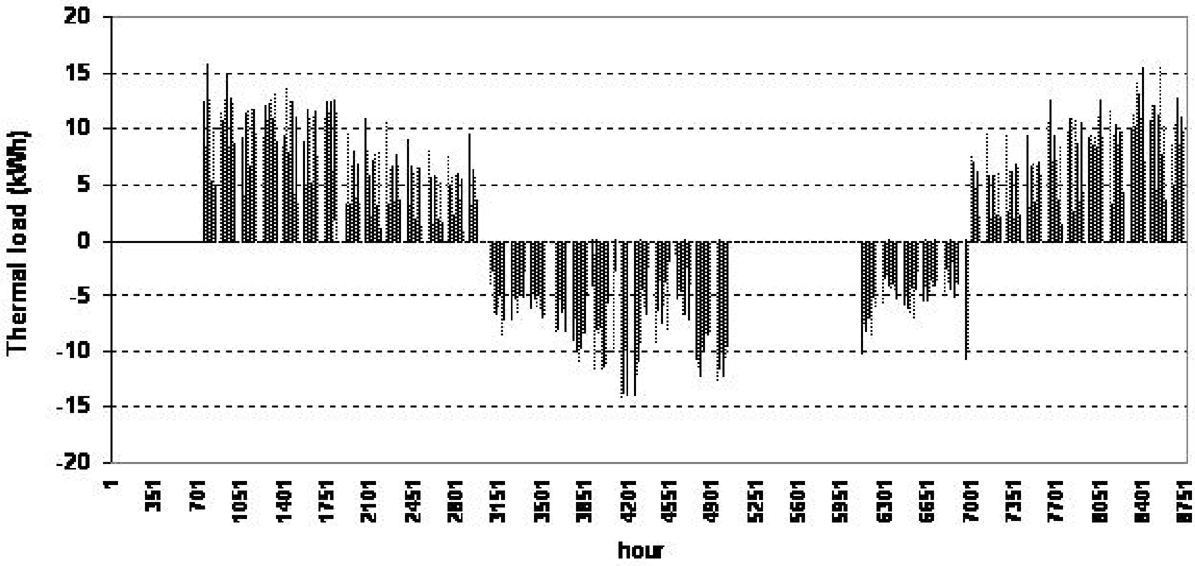

Figure 3: Measured thermal loads during one year of operation of GeoCool plant. Numbers on the horizontal axis mean the amount of hours from the beginning of the year up to a moment of the year. Positive values of thermal loads are associated to heating demand and negative values to cooling demand

3.4 Loads

To make a better comparison between the usual design procedure to predict the energy performance of the system and the experimental data measured, the simulation uses as input values the experimental thermal loads measured in GeoCool along a whole cooling season and a whole heating season. An Excel file type keeps these measured data (hourly thermal load during one year calculated from the experimental data). Figure 3 shows the experimental values of the thermal loads used in the simulation.

We need to calculate the inlet load temperature because this parameter is one of the heat pump model inputs. Thus we consider the internal circuit (hydraulic pipes that connect the heat pump with the fan coils) as a control volume where the power balance can be evaluated as:

$$\dot{m}_{load}\ Cp_{load}\,(T_{load,in} - T_{load,out}) = \dot{Q}_{ww} - \dot{Q} \qquad (14)$$

Where $\dot{Q}$ represents the experimental thermal loads measured and $\dot{Q}_{ww}$ is the heat pump capacity at current conditions. We assumed as initial condition 20ºC of pipes water temperature and a pipes volume of 0.5 m^3. Equation (14) is programmed in the Excel file.

Loads component gives heat pump component the control signals for running or stopping. We fix 45 ºC as stop temperature in heating and 12 ºC as stop temperature in cooling ($T_{load,\ out}$).

3.5 Model Outputs: Energy Performance Factor

The TRNSYS model calculates the energy performance factor in order to compare with the corresponding experimental values. The simulation program obtains this quantity following the same procedure outlined in section 2 to calculate the experimental value for the energy performance factor. Besides, the model plots the evolution of the main system parameters as ground and source temperatures, ground heat exchanger flow rate, control signals, devices power consumption, etc.

4. COMPARISON BETWEEN SIMULATION OUTPUTS AND EXPERIMENTAL RESULTS

We present in this section a comparison between the experimental data for the energy performance and the prediction coming from the simulation. The comparison is performed for a whole cooling season and for a whole heating season. The actual dates for the experiment are the following ones. The heating season comprises the periods from January 31, 2005 until May 6, 2005, and from October 17, 2005 until January 13, 2006. The cooling season comprises the periods from May 9, 2005 until July 31, 2005, and from September 1, 2005 until October 14, 2005. The simulation covers exactly the same periods. We compare the energy performance calculated for each day of operation (daily energy performance factor) and for the accumulated value from the beginning of each season up to a given moment. Figures 4 and 5 show these comparisons.

In figure 4 it is shown the accumulated value of the energy performance from one day of each season up to a given moment. Black lines correspond to the values obtained from the simulation and grey lines correspond to experimental measured values. From this figure we can see that the simulation outputs overestimate the experimental measures by a percentage between 15% and 20%. Taking into account that experimental errors for these quantities are estimated between 15% and 20% in principle we could conclude that in most cases experimental values and simulation estimations are compatible. Nevertheless, the tendency observed is very similar when comparing the curve obtained by joining experimental data with the one obtained by joining simulation results, indicating that there is an actual discrepancy between both quantities. To understand its origin we have done a sensitivity analysis of the simulation results to changes of its input parameter values. We observe that the estimated energy performance results are almost independent to changes on the ground description parameters. This property is expected because the length of GeoCool borehole heat exchanger was designed to be not sensible to changes on ground properties and, therefore, satisfy the requirements of the heat pump to always work in optimal conditions. We also observe an almost linear correlation between the heat pump nominal coefficient of performance and the estimations for the system energy performance coming from the simulation. Differences between experimental and simulated data can be explained as degradation of the heat pump performance for being used at partial load, i.e., the capacity at current conditions is higher than the thermal demand. This phenomenon can be incorporated in the simulation by multiplying the estimated COP by a degradation factor, CDF (Coefficient of performance Degradation Factor), which depends on the Partial Load Ratio (PLR, ratio between the thermal demand and the capacity at current conditions). A suitable parameterization for this degradation factor is:

$$CDF = 1 - \alpha(1 - PLR) \qquad (15)$$

From experimental data we have estimated that the value for the coefficient α is between 0.20 and 0.25. Taking into account this phenomenon, simulation outputs are compatible in value and in tendency with experimental results.

In figure 5 it is shown the energy performance factor calculated for each day of operation (daily performance factor, DPF). Black lines correspond to the values obtained from the simulation and grey lines correspond to experimental measured values. We have also included two grey-dashed lines to indicate the error bandwidth corresponding to each value of daily performance factor, for each date, the distance between the top grey-dashed line and the bottom grey dashed line represents the error bandwidth of the DPF value for this date. Estimated and experimental data show a similar behaviour to the one observed for the accumulated value of the performance factor presented in figure 4. The main difference we observe is a higher discrepancy between both values when the heating or cooling demand is very low (close to the dates in which the system changes operation from heating to cooling mode). This discrepancy is expected because low thermal loads produce low values for the partial load ratio and, then, a higher degradation of the heat pump coefficient of performance.

CONCLUSIONS

In this article it is presented a comparison between experimental and simulated results for the energy performance of a ground coupled heat pump system. The main conclusion of this work is that the simulation data overestimates the measured energy performance of the ground coupled system by a percentage between 15% and 20%. The relevance of this comparison relies in the fact that the performed simulation is based on a standard design procedure for ground coupled heat pump systems, using as input values parameters that are usually available for the engineer in charge of the system design. It is a remarkable result the fact that the standard design procedure based on TRNSYS simulation drives to an energy performance prediction quite close to the performance measured in the monitored ground coupled heat pump system. Furthermore, differences between experimental results and simulated outputs can be understood as degradation of heat pump performance for being used at partial load.

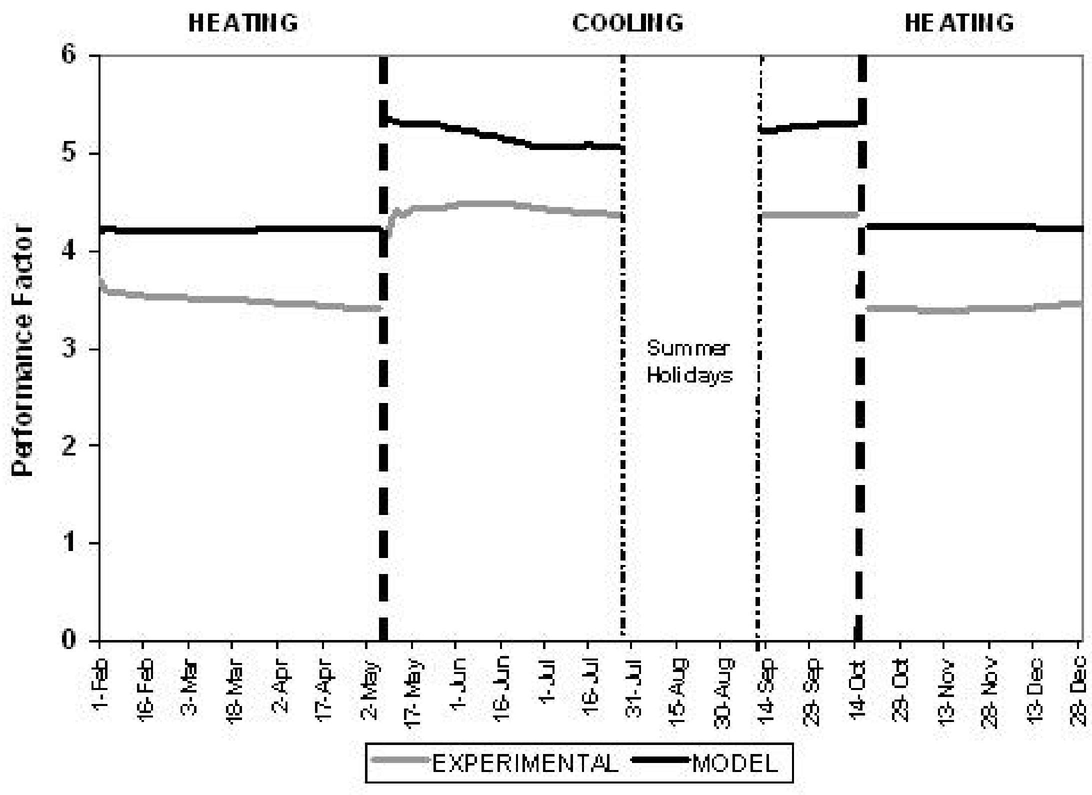

Figure 4: Comparison between experimental and simulation results for the performance factor of GeoCool geothermal plant

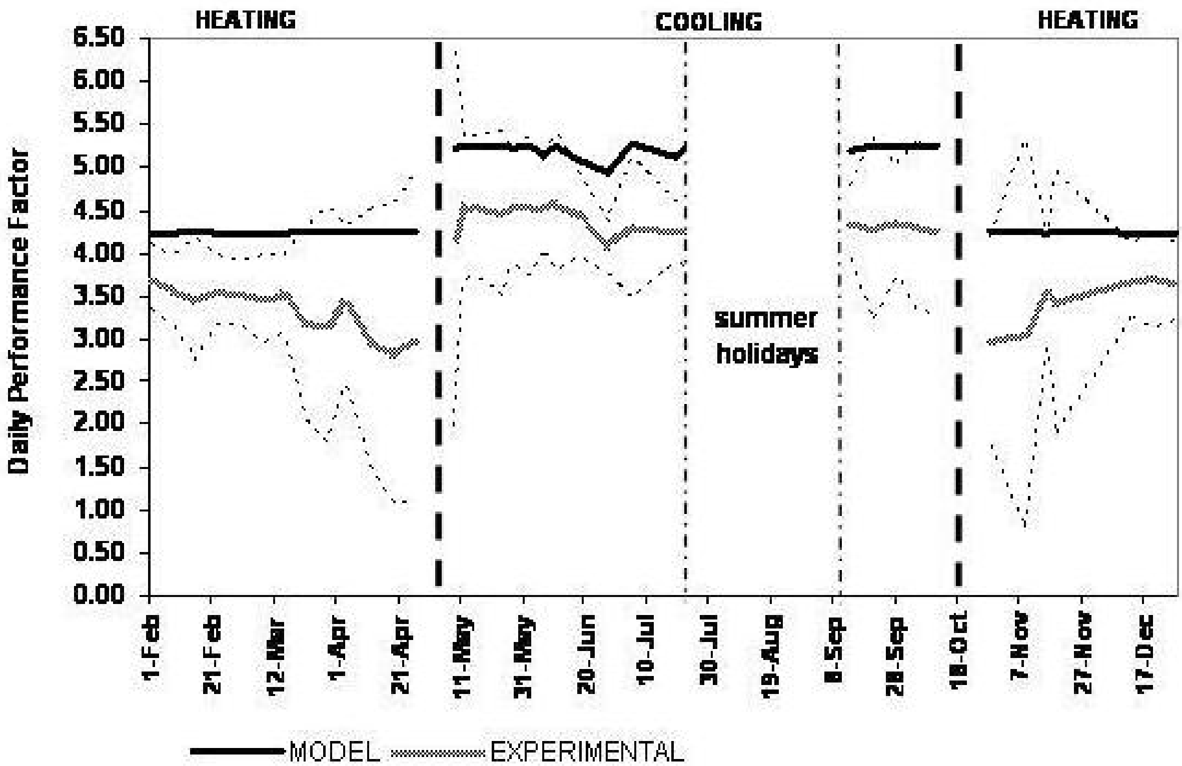

Figure 5: Comparison between experimental and simulation results for the daily performance factor of GeoCool geothermal plant. Errors for the experimental values of daily performance factor are represented by the distance between the top grey-dashed line and the bottom grey-dashed line

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