COMPARISON BETWEEN SIMULATION AND EXPERIMENTAL RESULTS FOR THE ENERGY PERFORMANCE OF GEOCOOL GEOTHERMAL EXPERIMENTAL PLANT

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ABSTRACT

The use of computer models for performance predictions has become almost essential in the design and management of ground coupled 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, focusing at the energy performance factor. We calculate the system energy performance factor of a monitored ground source 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 measured in GeoCool experimental plant (3.5 ± 0.6 for heating and 4.3 ± 0.6 for cooling).

1. INTRODUCTION

Ground-Coupled Heat Pumps represent a good alternative as system for heating and cooling buildings (see Urchueguía et al., 2008). When compared with standard technologies, these heat 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. The U.S. Environmental Protection Agency recognizes ground source systems as being among the most efficient and comfortable heating and cooling systems available today. The number of installed units worldwide, above 1 million, illustrates the high acceptance of this emerging technology in the Heating, Ventilation, & Air Conditioning market.

Simulation tools are widely used when designing ground coupled heat pump HVAC systems. Its predictions determine its final design. The purpose of this work is to compare a standard design procedure with the experimental results obtained on a monitored geothermal plant. 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.
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 quality of the models describing the ground coupled heat pump HVAC system. What we present in this study is the comparison between the performance factor 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. Finally in Section 4 we present and discuss the results, comparing simulation outputs with experimental data.

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 m². 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.

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.

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 (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 K. The mass flow meters are Danfoss Coriolis meters, model massflow 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 are collected by a data acquisition unit Agilent HP34970A with plug-in modules HP34901A.
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.

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 loads are calculated measuring the values $T_{in}$, $T_{out}$ and $m$ showed in Figure 1 with temperature sensors and a Coriolis meter. Using these values, we obtain the thermals loads by means of the following expression:

$$\dot{Q}(t) = \dot{h}_{out}(t) - \dot{h}_{in}(t) = mC_p[T_{out}(t) - T_{in}(t)]$$  \hspace{1cm} (1)

This function represents the difference between the input and output 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 is defined as the integral of expression (1). It represents the cooling or heating load demanded by the building during the time period $\Delta t$ starting at $T_0$ time.
\[ Q = \int_{t_e}^{t_e + \Delta t} \dot{Q}(t) dt \]  

(2)

Likewise, the system power consumption is calculated by integrating numerically the recorded power consumption (water to water heat pump (W_{ww}) and circulation pump (W_{cp})).

\[ W = \int_{t_e}^{t_e + \Delta t} (\dot{W}_{ww}(t) + \dot{W}_{cp}(t)) dt \]  

(3)

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

\[ PF = \frac{Q}{W} \]  

(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 (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.

![Figure 2. TRNSYS model used to simulate GeoCool plant](image)
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). 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 is on, the model calls the corresponding data file and calculates the coefficient of performance (COP), the energy absorbed ($Q_{\text{absorbed}}$) or rejected ($Q_{\text{rejected}}$) 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.

**Heating mode**

\[
\text{COP} = \frac{Q_{\text{ww,heating}}}{W_{\text{ww,heating}}} \tag{5}
\]

\[
Q_{\text{absorbed}} = Q_{\text{ww,heating}} - W_{\text{ww,heating}} \tag{6}
\]

\[
T_{\text{source,out}} = T_{\text{source,in}} - \frac{Q_{\text{absorbed}}}{m_{\text{source}}\, c_{p_{\text{source}}}} \tag{7}
\]

\[
T_{\text{load,out}} = T_{\text{load,in}} - \frac{Q_{\text{ww,heating}}}{m_{\text{load}}\, c_{p_{\text{load}}}} \tag{8}
\]

**Cooling mode**

\[
\text{COP} = \frac{Q_{\text{ww,cooling}}}{W_{\text{ww,cooling}}} \tag{9}
\]

\[
Q_{\text{rejected}} = Q_{\text{ww,cooling}} - W_{\text{ww,cooling}} \tag{10}
\]

\[
T_{\text{source,out}} = T_{\text{source,in}} + \frac{Q_{\text{rejected}}}{m_{\text{source}}\, c_{p_{\text{source}}}} \tag{11}
\]

\[
T_{\text{load,out}} = T_{\text{load,in}} + \frac{Q_{\text{ww,cooling}}}{m_{\text{load}}\, c_{p_{\text{load}}}} \tag{12}
\]

Where $Q_{\text{ww}}$ represents the heat pump heating or cooling capacity at current conditions, $W_{\text{ww}}$ means the power drawn by the heat pump in each mode.

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:
\[ W_{cp} = W_{\text{max, cp}} \frac{m_{\text{source}}}{m_{\text{max, source}}} = W_{\text{max, cp}} \frac{m_{\text{max, source}}}{m_{\text{max, source}}} \frac{f}{m_{\text{max, source}}} \] (13)

\( W_{\text{max, cp}} \) and \( m_{\text{max, source}} \) are the pump power consumption and the water mass flow when the pump is operating at full capacity and \( m_{\text{source}} \) 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’ (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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of boreholes</td>
<td>6</td>
</tr>
<tr>
<td>Borehole depth</td>
<td>50 m</td>
</tr>
<tr>
<td>Borehole radius</td>
<td>0.120 m</td>
</tr>
<tr>
<td>Storage thermal conductivity</td>
<td>1.6 W/m K</td>
</tr>
<tr>
<td>Storage Heat Capacity</td>
<td>2400 kJ/m$^3$/K</td>
</tr>
<tr>
<td>Outer radius of u-tube pipe</td>
<td>0.016 m</td>
</tr>
<tr>
<td>Inner radius of u-tube pipe</td>
<td>0.0131 m</td>
</tr>
<tr>
<td>Center to center half distance</td>
<td>0.035 m</td>
</tr>
<tr>
<td>Fill thermal conductivity</td>
<td>2.0 W/m K</td>
</tr>
<tr>
<td>Pipe thermal conductivity</td>
<td>0.42 W/m K</td>
</tr>
</tbody>
</table>

Table 1. Description parameters of the ground heat exchanger.

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.

### 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).
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 energy balance can be evaluated as:

$$m_{\text{load}} \cdot c_{p_{\text{load}}} (T_{\text{load,in}} - T_{\text{load,out}}) = \dot{Q}_{\text{in}} - \dot{Q}$$

(14)

Where $\dot{Q}$ represents the experimental thermal loads measured and $\dot{Q}_{\text{in}}$ is the heat pump capacity at current conditions. We assumed as initial condition 20°C of pipes water temperature and a pipes volume of 0.5 m³. 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 ($T_{\text{load, out}}$).

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

In figure 3 we show the comparison between the experimental data for the energy performance factor 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.

Looking at figure 3 we can see that the simulation prediction is quite close to the experimental results. In heating season the prediction overestimates approximately a 5% the measured values. In cooling season the tendency changes, the prediction underestimate approximately a 10% the experimental ones. Taking into account that the estimated errors for the experimental data are around the 15%, we can conclude that both results, experimental and simulated, are compatible. Nevertheless, it is not reasonable the tendency change between both seasons. What we will expect is that in both cases the simulation is overestimating the actual performance of the system. We think that the origin of this tendency change is due to the improvement of the commercial heat pump unit from the use of propane as refrigerant. As reported in GeoCool final publishable report (GeoCool, 2006) the coefficient of performance of the improved heat pump is 34% higher in cooling and about 15% higher in heating operation. We are working in this direction (Magraner, 2009) to perform a simulation including this characteristic in a new TRNSYS module describing specifically the water to water heat pump of GeoCool geothermal plant.
Performance Factor

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REFERENCES


