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Efficiency improvement of a ground coupled heat pump system from energy management

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The installed capacity of an air conditioning system is usually higher than the average cooling or heating demand along the year. So, most of the time, the system is working under its actual capacity. In this contribution, we study the way to improve the efficiency of a ground coupled heat pump air conditioning system by adapting its produced thermal energy to the actual thermal demand. For this purpose, an air conditioning system composed by a ground coupled heat pump and a central fan coil linked to an office located in a cooling dominated area was simulated, and a new management strategy aiming to diminish electrical consumption was developed under the basic constraint that comfort requirements are kept. This strategy takes advantage of the possibility of managing the air flow in the fan, the water mass flows in the internal and external hydraulic systems, and the set point temperature in the heat pump to achieve this objective. The electrical consumption of the system is calculated for the new management strategy and compared with the results obtained for a conventional one, resulting in estimated energy savings around 30%.

1. Introduction

It is a well-known fact that building equipments are responsible of around the 40% of all greenhouse gas emissions produced in developed countries, being approximately 60% produced by cooling and heating systems [1–3]. In this context, the development of air conditioning (HVAC) systems should be oriented to improve its energy efficiency and to reduce its environmental impact.

Ground Coupled Heat Pumps (GCHP) systems represent a technically viable technology for heating, cooling and domestic hot water systems in buildings [4–9]. They offer several interesting characteristics for the potential user, such as a lower electrical demand and maintenance requirements than conventional air to water heat pump systems and, therefore, lower annual cost [10–13]. From a non economical point of view, they offer competitive levels of comfort compared with standard technologies, reduced noise levels and visual impact, savings of greenhouse gas emissions and reasonable environmental safety. Furthermore, the Environmental Protection Agency (EPA) recognizes ground source systems among the most efficient and comfortable heating and cooling systems available today [14]. A proof of the goodness of this technology is the amount of installed units worldwide, estimated in 1.1 million [15].

In the standard design of an air conditioning system, the references taken to estimate the heating and cooling capacity of the system to be installed are usually based on the coldest and the warmest day along the year. A ground coupled heat pump air conditioning system can be designed to meet the whole load or just a part of it, using an auxiliary system to achieve comfort conditions in days in which thermal demand is higher than the capacity of the heat pump system. In both cases, the thermal energy required by the thermal load is under the actual capacity of the system during most part of the time. In this context, the development of strategies for the operation of the air conditioning system and, particularly, for the system based on the ground coupled heat pumps, allowing to adapt the thermal energy generated by the system with the thermal load is a good way to improve the system energy efficiency while satisfying the thermal comfort [16–19]. An approach to achieve this objective based in the combination of the ground coupled system with other production system and in the decoupling of energy production from energy distribution was presented in Ref. [20].

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Nomenclature

P_{pump}	Circulation pump electrical power consumption
$P_{rated,pump}$	Rated circulation pump electrical power consumption
P_{fan}	Fan electrical power consumption
$P_{rated,fan}$	Rated fan electrical power consumption
Q_{load}	Load met by the heat pump
P_{HP}	Heat pump electrical power consumption at current conditions
G	Heat pump capacity at current conditions
G_{rate}	Heat pump rated capacity
G_{ratio}	Heat pump capacity at current conditions divided by the rated capacity
COP	Heat pump coefficient of performance at current conditions
COP_{rate}	Heat pump rated coefficient of performance at current conditions
COP_{ratio}	Heat pump COP at current conditions divided by the rated COP
f_{flp}	Heat pump fraction of full load power
PLR	Heat pump partial load ratio
T_{set}	Set point temperature – desired outlet temperature of fluid in the heat pump fluid stream
$T_{load,in}$	Inlet temperature of fluid in the heat pump load stream
$T_{GHE,in}$	Inlet temperature of fluid to the ground heat exchanger
$T_{GHE,out}$	Outlet temperature of fluid from the ground heat exchanger
T_a	Temperature of the surrounding ground
β	dumping factor
α_v	heat transfer coefficient between the fluid and the surrounding ground per unit of volume
α_p	heat transfer coefficient between the fluid and the surrounding ground per unit length of pipe
V	Volume of storage
L_p	total pipe length in the storage volume
C_f	Volumetric heat capacity of the fluid
Q_f	Total fluid flow rate in the ground heat exchanger
$\dot{m}_{water}$	Mass flow rate of fluid passing through the circulation pump
$\dot{m}_{rated,water}$	Maximum mass flow rate of fluid that can pass through the circulation pump
$\dot{m}_{water,IWP}$	Mass flow rate of fluid passing through the internal circulation pump
$\dot{m}_{water,FWP}$	Mass flow rate of fluid passing through the external circulation pump
Cp_{water}	Specific heat of fluid
$\dot{m}_{air}$	Mass flow rate of air passing through the fan
$\dot{m}_{rated,air}$	Maximum mass flow rate of air that can pass through the fan
$\dot{m}_{con,fc}$	Flow rate of condensate draining from the coil
$h_{air,in,fc}$	Enthalpy of air entering the coil
$h_{air,out,fc}$	Enthalpy of air exiting the coil
$h_{con,fc}$	Enthalpy of condensate draining from the coil

This contribution tries to achieve the same objective just taking advantage of the possibility of managing the operational variables of the ground coupled heat pump system.

Following this idea, the aim of this work is to evaluate the energy savings that a new management strategy can produce in an HVAC system composed by a ground coupled heat pump and a central fan coil linked to a standard office space. In this new management strategy, the air mass flow in the fan, the water mass flow in the internal and external hydraulic system and the set point temperature in the heat pump, usually fixed in conventional strategies, have the possibility of a continuous regulation that allows us to design a more efficient way to achieve the desired thermal comfort.

This new management strategy is based on five capacity levels developed from the total electrical power equation of the HVAC system. In our particular case, this equation indicates that to achieve energy savings is desirable to work with low water flows. For this reason, the new management strategy tries to achieve a steady state in which the water mass flow is maintained at the lower level that guarantees the production of enough thermal energy to satisfy the thermal demand.

An office space in a cooling dominated area is modelled to evaluate in these conditions the energy performance of the ground coupled heat pump HVAC system when it is managed by the new management strategy and by a conventional one. The thermal comfort criterion which has to be satisfied is the Predicted Mean Vote index (PMV). This comfort index predicts the mean value of votes of a large group of people in the Thermal Sensation Scale and it is defined by the ISO7730-1994 standard [21].

We compare the annual electrical energy consumption of the HVAC system when it is managed by our new management strategy and by a conventional one and an evaluation of its energy efficiency is presented. We also analyze the factors which allow improving the energy efficiency of the air conditioning system by the new management strategy.

2. Simulated system

In this section, we present a description of the simulated office area as well as the PMV index which is the criterion used to evaluate the thermal comfort. Afterwards, we describe the ground coupled heat pump system linked to the office area, the energy model of the employed devices, the new management strategy and the conventional one. Finally, these systems are simulated using TRNSYS software package [22].

2.1. Simulated office area

The simulated office area comprises 108 m^2; (12 m $\times$ 9 m) with two windows in the façades north and south and three in the façades east and west. To perform the simulation the office area is characterized by its building materials, its dimensions, distribution and orientation. There are four different kinds of construction elements: external walls, floor, roof and window glasses. External walls are defined as ventilated façades composed by four elements: perforated brick, 5 cm of insulation, air chamber and a Naturex plate cover; its global conductivity is 0.51 W/m^2 K. The floor and the roof are built with hollow blocks with 5 cm of insulation; its global conductivity is 0.51 W/m^2 K. Finally, the window is composed by a glass, with solar radiation transmissivity equal to 0.837 and conductivity equal to 5.74 W/m^2 K, and a window frame with conductivity equal to 0.588 W/m^2 K. The windows size is 1.5 m^2, dedicating a 15% of this area to the frame surface. The internal and external shadow factor for these windows is estimated in 0.7.

These parameters are included in the TRNSYS software package through the TRNBuild tool specifically designed to simulate the thermal behaviour in a multi-zone building area. Finally, the weather database of the Spanish city of Valencia is used to characterize the Mediterranean coast weather.