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A simulation-based analysis of variable flow pumping in ground source heat pump systems with different types of borehole heat exchangers: A case study

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ABSTRACT

A simulation model of ground source heat pump systems has been used to investigate to what extent a variable flow of the heat-carrier fluid of the ground loop affects the energy efficiency of the entire system. The model contemporaneously considers the borehole heat exchangers, the heat pump, the building load, and the control strategies for the circulation pumps of the ground loop. A constant speed of the circulation pumps of the ground loop was compared with a variable flow controlled by means of a constant temperature difference across the heat pump on the ground side considering the load profile of an office building located in North Italy. The analysis was carried out for a single U-tube, double U-tube and coaxial pipe heat exchangers. The control strategies adopted to manage the flow rate of the heat-carrier fluid of the ground loop affect both the heat exchange rate of the borehole field and the heat pump's long-term energy efficiency. The simulations show considerable differences in the system's seasonal energy efficiency. The constant speed of the circulation pumps leads to the best results as far as the heat pump's energy performance was concerned, but this advantage was lost because of the greater amount of electrical energy used by the circulation pumps; this, of course, affects the energy efficiency of the entire system. The optimal solution appears then to be a constant temperature difference in the heat-carrier fluid across the heat pump.

1. Introduction

Efforts to reduce CO_2 emissions have become a pivotal environmental priority of this century. Recently the COP21 Climate Conference in Paris [1] reaffirmed the goal of keeping average warming below 2 °C and the long term goal of ultimately limiting the increase to 1.5 °C. Moreover, according to the Paris agreement, the goal of net greenhouse gas neutrality should be achieved during the second half of this century.

Buildings are responsible for about 40% of total energy consumption in Europe [2] and similar values are also found in other countries. To decrease this value some of the open options are those of improving the quality of buildings' envelopes or of using energy-efficient heating and cooling technologies based on renewable energies. In the latter case, heat pumps may significantly contribute to reaching these goals.

Ground source heat pumps (GSHPs) use the ground or groundwater as a heat source or sink. The most frequently used GSHP system is the closed loop type with vertical ground heat exchangers or borehole heat exchangers in which the heat-carrier fluid flows exchanging heat with the ground and the refrigerant fluid of the heat pump. The design of a GSHP system is of critical importance because design choices affect the entire system's energy performance and operating conditions; this is a particularly important consideration for a GSHP system with respect to the others because it has higher installation costs.

Many researchers have extensively investigated the performance of GSHPs and focused on ground heat exchangers. Several analytical and numerical models have been developed to simulate the thermal behaviour of ground heat exchangers [3], and some studies analysing the optimal design and control of GSHP systems can be found in the literature [4]. Kizilkan and Dincer [5], for example, presented an energy and exergy analysis of the borehole thermal energy storage system used for heating and cooling campus buildings of University of Ontario Institute of Technology. The analysis, which was carried out for the heating season alone, found that the exergy efficiency of the entire system was about 41% and considerable energy savings could be achieved by determining and reducing the exergy destruction within the system's components.

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Nomenclature

a	thermal diffusivity (m^2/s), surface absorptance (–)
c	specific heat (J/(kg K))
C	volume heat capacity (J/K)
COP	coefficient of performance in heating mode (–)
D	diameter (m)
E	energy rate (kWh), tolerance (W)
EER	coefficient of performance in cooling mode (–)
h_{ext}	convection heat transfer coefficient at ground level (W/(m^2 K))
i	ground discretization index in radial direction
j	ground discretization index in vertical direction
L	length (m)
L_{bore}	borehole length (m)
$\dot{m}$	mass flow rate (kg/s)
P	power (W)
Q	heat rate (W)
r	radius (m)
r_{max}	radius from axis borehole beyond which the undisturbed ground is considered (m)
R	thermal resistance (K/W)
R_{ext}	convection thermal resistance at ground level per unit area ((m^2 K)/W)
R_{p0}	thermal resistance between the pipe and borehole wall ((m K)/W)
R_{ppA}	thermal resistance between adjacent pipes ((m K)/W)
R_{ppB}	thermal resistance between the opposite pipes ((m K)/W)
$SCOP$	seasonal coefficient of performance in heating mode (–)
$SEER$	seasonal coefficient of performance in cooling mode (–)
T	temperature (K)
T_{ext}	external air temperature (K)
T_g	undisturbed ground temperature (K)
T_{sky}	sky temperature (K)
$\dot{V}$	volume flow rate (m^3/s)
w	velocity (m/s)

Greek symbols

ε	surface emittance (–), efficiency (–)
ζ	drag coefficient (–)
λ	thermal conductivity (W/(m K))
η	pump efficiency (–)
ρ	density (kg/m^3)
τ	time (s)
Δp	pressure loss (Pa)
$\Delta\tau$	discretization time step (s)
Δz	length of control volume in vertical direction (m)
ΔT	temperature difference (K)

Subscripts

b	borehole, borehole zone, building
d	deep zone
C	carnot cycle
c	cooling
$cond$	condenser, condensing
el	electrical
$equip$	equipment
$evap$	evaporator, evaporating
f	fluid
g	ground
h	heating
hp	heat pump
i	inside
in	inlet
nom	nominal
out	outlet
r	radial direction
s	surface zone
sys	system
tot	total
z	depth direction

Hénault et al. [6] recently presented a strategy to optimize the net present value of a hybrid ground-coupled heat pump system making use of a spectral-based simulation tool in order to predict the heat pump performance on an optimization algorithm.

Urchueguía et al. [7] compared a ground source heat pump system and a conventional air to water heat pump one using an experimental test carried out at the Universidad Politécnica de Valencia, Spain. The authors found that the former is a viable and energy efficient alternative to conventional systems for heating and cooling applications in Southern Europe. They nevertheless reported that the cost of electricity consumption of auxiliary elements such as circulation pumps and fan–coils was rather high and suggested that the system's efficiency and control strategies needed to be improved.

When control strategies in GSHPs are being examined, attention is usually focused on the distribution system on the building side and not on the ground one because the user's thermal satisfaction is the primary objective as far as the air conditioning system is concerned. Many studies in the literature have focused on the control from the point of view of the heat pump, especially with regard to the main variables on the building side in heating and cooling modes.

Zhao et al. [8] investigated the output capacity of a ground source heat pump system using a variety of methods in the attempt to match the thermal capacity with the building load. The study, which focused on a small-size heat pump and a particular refrigerant fluid, was based on a theoretical and experimental analysis. They found that the best method was the one that adjusted the compressor's rotation speed using a transducer.

Karlsson and Fahlen [9] studied the energy performance of a variable-speed capacity control instead of a conventional intermittent operation mode for domestic ground source heat pumps. The analysis showed how energy efficiency is influenced by the compressor's variable-speed capacity control. The authors found that in order to take full advantage of the capacity control, it was important to achieve the correct relationship between the refrigerant and the heat-carrier fluid flows.

Corberan et al. [10] investigated the effect of variations in the mass flow rate of the heat-carrier fluid of the external loop on both the thermal capacity and energy efficiency of a heat pump in the cooling mode by means of experimental tests carried out in the laboratory. The authors found that the flow variation on the evaporator side particularly affected its cooling capacity, whereas the flow variation on the condenser side particularly affected energy efficiency. Granryd [11] also investigated the effects of the flow rate of the external heat-carrier fluid (air or liquid) on the condenser and evaporator side. The primary objective of his work was to define simple analytical equations to be used to evaluate optimum flow rate.

Madani et al. [12] used three common control methods to manage an on/off controlled GSHP system: the so-called "constant hysteresis", the "floating hysteresis" and the "degree-minute" methods. These types of controls were used in the building side distribution system to switch on/off the heat pump. In all the cases,