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Analysis of operating modes of a ground source heat pump with short helical heat exchangers

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ABSTRACT

This study focuses on different operating modes of a ground source heat pump system in residential buildings. Ground coupling was made using a closed loop system consisting of a helical shaped pipe installed at a shallow depth. Few studies have examined this particular ground heat exchanger.

The analysis was carried out using a detailed numerical model capable of considering the geometry of the helical ground heat exchanger as well as the effects of axial thermal conduction and the weather at ground level, variables which cannot be ignored when shallow depths are being investigated. Field measurements were used to validate the model before it was utilized. In addition, the simulation tool considered the entire ground source heat pump system, including both the borehole field and the heat pump.

The energy efficiency of the heat pump in three operating modes (continuous daytime, continuous nighttime, and intermittent mode) over a ten year period was analysed. The simulations were performed in two different climatic zones maintaining the daily energy load of the building unmodified. Finally, the effect of the grouting material of the helical ground heat exchanger and of the diameters of both the borehole and the helix on the system's energy performance was also investigated. Results indicated that the seasonal energy efficiency of the heat pump was approximately the same for the three operating modes and that energy efficiency was nearly constant during the day when the system was operating on an hourly intermittent basis. When the borehole diameter was smaller, the reduction in the heat exchange surface needed to be balanced by a thermally enhanced grouting material.

1. Introduction

The energy required to keep buildings heated and air-conditioned has become an important environmental challenge [1]. Heat pumps are considered the most effective systems for heating and cooling buildings as they extract heat from the heat source in the heating mode and work as chillers injecting the heat load of the building into the heat "sink" in the cooling one. The most widespread source or sink is the ambient air. As is well known, the temperature of the heat source-sink affects the energy efficiency of the heat pump. Just as the ambient air temperature changes throughout the year depending on the weather, even the energy efficiency of the heat pump is variable over time. Moreover, defrosting is a problem that can occur in the heating mode when ambient air is used as heat source.

Ground source heat pump (GSHP) systems use the ground whose temperature is not heavily dependent on the ambient temperature but on the first upper 10–15 m [2]. Ground temperature can, however, increase or decrease over long periods of time because of the energy imbalance between the building's heating and cooling loads that can degrade the heat pump's performance. The long-term thermal performance of a GSHP system can be investigated using multi-year integrated computer simulations that can analyse both the heat pump and the ground heat exchangers.

A number of simulation tools that can carry out integrated computer simulations are available. The most widespread are EnergyPlus [3] and TRNSYS [4], and both can simulate several HVAC systems. EnergyPlus uses *long-* [5] and *short-time g-functions* [6] to handle simulations of borehole heat exchangers. TRNSYS includes three main models to simulate borehole heat exchangers. The first, an approach proposed by Hellström [7] (Type 557), considers axial heat conduction but ignores borehole thermal capacitance. The second one, proposed by Huber and Wetter [8] for double U-tube heat exchangers (Type 451), does not include axial heat conduction. The last one implements the *long-time g-functions* method developed by Eskilson [5] (Type 281) but does not consider the contribution of the borehole thermal capacitance. None of the

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Nomenclature

a	thermal diffusivity (m^2/s), surface absorptance (–)
C	volume heat capacity (J/K)
COP	coefficient of performance (–)
D	diameter (m)
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)
m	maximum discretization index in vertical direction
n	maximum discretization index in radial direction
Q	power or heat flow (W)
r	radius (m)
r_{max}	radius from axis borehole beyond which the undisturbed ground is considered (m)
R	thermal resistance (K/W)
R_b	borehole thermal resistance per unit length (m K/W)
R_{ext}	convection thermal resistance at ground level per unit area (m^2 K/W)
$SCOP$	seasonal coefficient of performance (–)
T	temperature (K)
T_{ext}	external air temperature (K)
T_g	undisturbed ground temperature (K)
T_{sky}	sky temperature (K)
z	depth (m)

Greek symbols

ε	surface emittance (–)
λ	thermal conductivity (W/(m K))
τ	time (s)
$\Delta\tau$	discretization time step (s)
Δz	length of control volume in vertical direction (m)

Subscripts

b	borehole, borehole zone
d	deep zone
c	cooling
el	electrical
g	ground
h	heating
in	inlet
o	outside
out	outlet
r	radial direction
s	surface zone
z	depth direction

approaches takes into consideration heat transfer via convection and radiation along the ground surface.

Parisch et al. [9] used the three models included in TRNSYS to compare measurements and numerical simulations over a short time period using a commercial finite element software considering a common U-tube borehole heat exchanger; according to their study, the simulation results underestimated the injected heat load by 50% when the borehole thermal capacitance was not modelled.

Montagud et al. [10] used TRNSYS to analyse an entire GSHP system consisting of six vertical boreholes containing a single U-tube and compared simulation results with experimental measurements for one day in the cooling mode of a reversible water-to-water heat pump with nominal heating and cooling capacities equal to 18 kW and 14 kW, respectively. Wu et al. [11] used TRNSYS (Type 557) to investigate the effect of borehole free cooling of ground source absorption heat pumps in three cities in China; the results of their simulations showed that additional cooling reduced the deterioration of the system's energy performance caused by the thermal imbalance of the building load profiles.

Other authors have used numerical and analytical approaches to analyse GSHPs. Kurevija et al. [12] used *long-time g-functions* in order to investigate the thermal interference between the boreholes with single U-tube in two grids (7×6 and 21×2) in the city of Zagreb; a constant energy efficiency of the heat pump was used in their analysis. Kizilkan and Dincer [13] conducted an energy and exergy analysis of a GSHP system located in Ontario (Canada); they concluded that the system's performance was slightly improved in the heating mode when the fluid temperature entering the heat pump was higher.

Some studies have extensively investigated the performance of a GSHP from the heat pump point of view. Zhao et al. [14] presented a theoretical and experimental analysis in order to investigate the effects on the energy efficiency of the heat pump of several capacity control strategies (turning on/off compressor, controlling intake and discharge valves' on/off times, concentration ratios of the refrigerant mixture and compressor's speed); in their study, the ground loop was considered making use of a water tank. Lee [15] analysed the part-load performance of a GSHP system equipped with a double U-tube borehole heat exchanger that was simulated with a three-dimensional implicit finite difference model; the analysis focused on the variable-speed compressor. Madani et al. [16] used variable and single speed compressors to carry out an in-depth study of capacity control in GSHP systems based on a comparative analysis of on/off controlled and variable capacity systems. Del Col et al. [17] evaluated the performance of a GSHP of an office building consisting of four 80 m long vertical boreholes (two with single U-tube and two with double U-tube) during the heating season; they presented experimental data and developed a numerical model based on lookup tables of the main components of the system. The work of Del Col et al. [17] focused on how the performance of the heat pump was affected in partial loads, analysing the effect of the variable speed; in their study, the thermal behaviour of borehole heat exchangers was simulated separately from the heat pump by means of a commercial software [18].

The present study focuses on control strategies for a GSHP in a residential building from the ground heat exchanger point of view; in particular, this work investigates how the interaction between the ground and short borehole helical heat exchangers can affect the energy performance of the entire system. The main disadvantage of horizontal ground loop systems is the large ground area that is required for the installation; this explains why vertical ground heat exchangers are preferable. The geometry of the ground heat exchanger can be optimised to improve thermal performance and to reduce installation costs by limiting the borehole length; this is the rationale behind the choice of helical shaped pipe heat exchangers. As helical ground heat exchangers have diameters that are thicker and depths that are shorter than conventional borehole heat exchangers with a single or double U-tube, the borehole thermal capacitance and axial heat conduction cannot be neglected [19]. Shallow geothermal energy (up to a depth of 10–15 m) has not yet attained a wide market penetration despite its great potential and numerous advantages which are clearly