



Performance analysis of short helical borehole heat exchangers via integrated modelling of a borefield and a heat pump: A case study



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HIGHLIGHTS

- A new model to evaluate the efficiency of the whole GSHP system is presented.
- The model considers the interaction between the ground and the environment.
- Two types of vertical ground heat exchangers are analyzed: helix and 2U-tube.
- They are analyzed in the same operating conditions for two Italian climates.
- With helical shaped pipe a shorter total borehole depth is required.

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ABSTRACT

This paper presents a new simulation tool package that calculates the energy efficiency of an entire Ground Source Heat Pump (GSHP) system. The package consists of two detailed models of borehole heat exchangers and heat pump equipment coupled in a single well-integrated calculation tool.

It was used to analyze two types of ground heat exchangers in the same operating conditions for two Italian climates. Research focused on comparing a short helical-shaped pipe configuration with the more widespread and longer double U-tube. Analysis was carried out at the same energy exchange rate with the ground and addressed the difference in total borehole depth. The package also took into account the effects of the weather on the heat transfer between the heat exchanger and the surrounding ground.

Analysis found that a much shorter total borehole depth was needed for the helical-shaped pipe, which consequently reduces installation costs. Therefore, this configuration may be a suitable alternative to conventional U-shaped tubes, especially for new residential housing with low energy loads and where deep probe drilling is not possible. Finally, this paper also investigates the influence of the axial effects in the ground on the seasonal energy efficiency of the whole system.

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1. Introduction

A heat pump is one way to increase the energy efficiency of a building's heating and cooling systems [1–3]; it thus promotes the use of renewable energy and reduces primary energy consumption.

Ground Source Heat Pump (GSHP) systems are a suitable alternative to more widespread heat pump systems since they are designed to take advantage of the ground's favourable and relatively constant temperature. These systems generally use a heat pump both to heat and cool buildings; the ground acts as a heat

source in heating mode and as a heat sink in cooling mode. The present study focuses on the application of a GSHP system with vertical borehole heat exchangers (BHEs) to exploit the thermal interaction between a heat pump and the ground.

Literature reports a range of activities that investigate predictive models for the ground's thermal behaviour. Some models consider the long-term thermal drift in the ground brought about by the heat exchange between BHEs and the surrounding ground [4–6]. Other models and tools have been developed to take into account thermal exchange in the short- and medium-term [7–9]. Commercial Finite Element Method (FEM) tools are also an option. These tools are either designed in-house or commercially available, and are built for unlimited time analysis and a full 3D simulation of the thermal process. Nevertheless, their advantages are very often

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Nomenclature

a	thermal diffusivity (m^2/s), surface absorptance (–)
C	volume heat capacity (J/K)
COP	coefficient of performance (–)
E	temperature tolerance in the iterative calculation ($^\circ\text{C}$)
h_{ext}	convection heat transfer coefficient at earth surface ($\text{W}/(\text{m}^2 \text{K})$)
I	incident solar radiation (W/m^2)
i	ground discretization index in radial direction
j	ground discretization index in vertical direction
L_{bore}	borehole length (m)
L_d	thickness of deep zone (m)
L_s	thickness of surface zone (m)
m	maximum discretization index in vertical direction
n	maximum discretization index in radial direction
Q	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_{ext}	convection thermal resistance at earth surface ($\text{m}^2 \text{K}/\text{W}$)
R_{p0}	thermal resistance between pipe inside surface and borehole wall in double U-tube per unit length ($\text{m K}/\text{W}$)
R_{ppA}	thermal resistance between adjacent pipes in double U-tube per unit length ($\text{m K}/\text{W}$)

R_{ppB}	thermal resistance between opposite pipes in double U-tube per unit length ($\text{m K}/\text{W}$)
T	temperature (K)
T_{ext}	external air temperature (K)
T_g	undisturbed ground temperature (K)
T_{sky}	sky temperature (K)
$T_{-\Delta\tau}$	temperature at previous time step (K)
T_0	borehole wall temperature (K)
U	thermal transmittance ($\text{W}/(\text{m}^2 \text{K})$)
z	depth (m)

Greek symbols

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

Subscripts

b	borehole, borehole zone, building
d	deep zone
g	ground
hp	heat pump
in	inlet
out	outlet
r	radial direction
s	surface zone
z	depth direction
w	heat carrier fluid

counteracted by the need of specialists to manage pre- and post-processing operations and to provide a detailed characterization of the ground's thermal and physical proprieties.

This study analyzes a helical-shaped heat exchanger which, we believe, will require shorter total borehole depth (and consequently lower drilling costs) than the more commonly adopted U-tube ground heat exchangers. Nevertheless, the more compact helical-shaped heat exchanger also needs to be studied carefully to avoid unexpected thermal disturbances in the surrounding ground. The theoretical study of a less conventional and more critical component is, however, bound to entail more refined modelling techniques for axial thermal conduction in the ground and for the thermal exchange mechanisms between helical BHE and the ground. We also expect that a much stronger coupling will be needed between the BHE and the heat pump in this case. Some dedicated studies on helical-shaped heat exchangers are referenced in the available literature. Park et al. [10] performed FEM and analytical studies on this configuration and they compared their results with the experimental ones given by a thermal response test. Furthermore, they modified the analytical solutions performed by Man et al. [11] and Cui et al. [12] by adding a finite line source model that considered the effect of the heat flow from the non-helical pipe (i.e. in that case, the return pipe) at the centre of the heat exchanger.

Rabin and Korin [13] made a similar contribution. They modelled the helical pipe with a series of horizontal rings with a constant pitch between them and they solved this model by means of the finite difference method; they also compared the results with experimental data obtained from field tests.

Li and Lai [14] proposed an analytical approach to solve the heat conduction problem in infinite and semi-infinite anisotropic media with a helical line source, which was created by integrating a point source along the helix. In that study, they did not use the thermal

capacitance of grout, which was later introduced in Ref. [15]. Heat transfer at ground level was not analyzed.

Congedo et al. [16] carried out Computational Fluid Dynamics (CFD) simulations in order to investigate the horizontal configuration of a helical ground heat exchanger. Their work focused on comparing this set-up with linear and slinky ground heat exchangers during both the winter and summer in the typical climatic conditions of South Italy. They concluded that the helical-shaped heat exchanger had the best thermal performance.

This present study uses the CaRM model [17] which is designed to analyze the heat exchange process between BHEs and the ground, and requires the time history of the heat thermal load towards the ground to be calculated off-line beforehand. This analysis, however, did not fully account for the interaction between the heat pump and the ground, which influence each other through the BHE loop inlet and outlet temperatures and play a critical role when GSHP systems are used if they are not properly sized. Similarly, their reciprocal influence was disregarded between the HVAC plant and the building, in that it depends heavily on the climatic conditions. In conclusion, these studies required a further step, where the close link between heat pump and building and heat pump and ground was more realistically taken into account. Integration between these kinds of model has been dealt with specialised literature. Gupta and Irving [18] integrated a heat pump regression model into a BREDEM package [19], and Self et al. [20] integrated ground models with a heat pump model involving an economizer.

Against this background, the studies in this article also involved a fundamental, preliminary step that integrated previously developed models of heat pumps and BHEs. The resulting tool, named GeoHP-Calc, was used to compare two BHE set-ups: a double U-tube and a short helical one, under real climatic conditions.

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