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Research paper

Geothermal helical heat exchangers: Coupling with a reversible heat pump in western Europe

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HIGHLIGHTS

- Two exchangers model are compared: horizontal rings model and annular cylindrical conduit.
- The freezing of the subsoil is analyzed.
- The natural thermal load of the ground is studied.
- The thermal behavior in both long and short terms is investigated.
- Optimization rule is proposed to design the geothermal helical heat exchangers.

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ABSTRACT

This paper presents a computational analysis of geothermal heat pump used to assess the thermal needs of a 120 m^2 low-energy house. Helical heat exchangers are used to extract or inject heat into shallow subsoil. Two 2D-axisymmetric models of helical heat exchangers are compared. The frozen of the subsoil such as its thermal relaxation during the summer are analysed. The performance of the exchangers is being studied over a 10-year period. The impact of the heat-pump operating modes (short cycles vs. long cycle) on the system efficiency is assessed, and the influences of the subsoil properties and of the geometry of the geothermal exchangers are further studied. A sizing law relating the number of exchangers to be used and their height/diameter is proposed.

1. Introduction

"Very low enthalpy" geothermal resources are part of the renewable energies that one can use for heating and cooling buildings [1,2,3]. These resources are available throughout the year and everywhere. They require a heat pump, whose market is growing in Europe, with more than a million units installed over the last few years. Applications include the heating and cooling of buildings, the production of domestic hot water, and even the thermal unload of solar installations in summer. Several types of geothermal exchangers exist: the most widespread are the "borehole heat exchangers" [4], but other kinds can be used instead, such as horizontal loops [5], helical heat exchangers [6,7], or energy piles [3]. Helical heat exchangers are generally cylindrical. Their reduced height and diameter (typically 2.5 m and 1 m respectively) allow the use of traditional excavator for their installation in the ground. The upper part is generally placed 1 m below the ground level in order to take advantage of the thermal potential of the subsoil and the ground heat recharging during summer [8]. Helical heat exchangers offer a compromise between borehole heat exchangers

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Nomenclature

Latin letters

a	thermal diffusivity ($m^2\ s^{-1}$)
c_p	specific heat ($J\ kg^{-1}\ K^{-1}$)
E	thermal effusivity ($J\ K^{-1}\ m^{-2}\ s^{-1/2}$)
Fo	Fourier number (–)
H	height of the exchanger (m)
h	convective heat transfer ($W\ m^{-2}\ K^{-1}$)
L	specific latent heat ($J\ kg^{-1}$)
Nu	Nusselt number (–)
P	power (W)
q_v	volumetric flow rate ($m^3\ s^{-1}$)
R	radius of the exchanger (m)
R_{th}	thermal resistance ($K\ W^{-1}$)
r	radius (m)
T	temperature (K)
t	date (s)
z	depth (m)

Greek letters

β	auxiliary coefficient (–)
η	ratio of water at liquid state (–)
κ	volume fraction of water in the underground (–)
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
ρ	mass density ($kg\ m^{-3}$)
υ	damping (–)
φ	heat flux density ($W\ m^{-2}$)
ω	annual pulse ($rad\ s^{-1}$)

Letters with special subscripts

h_{tot}	convective and radiative heat transfer ($W\ m^{-2}\ K^{-1}$)
L_{tot}	helical length of the exchanger (m)
r_e	external radius of the pipe (m)
r_i	internal radius of the pipe (m)
T_{amp}	yearly amplitude of the ground-level temperature (K)
T_{ext}	ambient air temperature (K)
T_{moy}	mean ground temperature (K)
T_{in}	inlet temperature (K)
T_{out}	outlet temperature (K)
T_{ω}	period of a heat pump cycle (s)
t_c	coldest day (s)
t_{ini}	initial time (s)

Subscripts

f	heat transfer fluid
flow	flow
ice	solid water
liq.wat	liquid water
mat	“dry matrix” of the underground
mix	multi states
pipe	wall of the pipe
s	soil (next to the exchanger)
∞	infinite

Accentuation

$\tilde{}$	undisturbed by the exchanger

and horizontal loops: they do not require such a large area as horizontal loops and are claimed to be cost effective. Furthermore, their operation has no impact on the building structure as it may sometime be the case with energy piles. Helical heat exchangers appeared on the market the last few years but the number of studies related to their operation is quite limited. This paper is a contribution to the study of such new compact exchangers.

The underground is usually described in a 2D axisymmetric way, considering the underground as a semi-infinite solid, spatially homogeneous, with thermal transfers occurring only by conduction. Its yearly temperature matches the heat equation, with an upper boundary condition corresponding to a sinusoidal variation of the upper temperature with a 1-year period. The problem of heat transfer can be solved with an equivalent electrical circuit of thermal resistances and capacitances [8]. This modeling usually doesn't consider the freezing of the subsoil that can appear during operation, as presented e.g. by Ref. [9]. However, the freezing of the subsoil locally impacts the physical properties of the subsoil and is accompanied by a release of energy, which mainly depends on the water content of the underground as shown in Ref. [10]. In this paper, the underground is considered as a homogeneous porous medium – the pores being full of water – with no coupling between moisture transfer and thermal conditions. Moreover, the phase change does not produce any volume change, and the thermal properties of the soil matrix are constant. Three regions are defined (freezing soil region, unfreezing soil region, and two-phase region), with moving interfaces where the phase changes occur. Actually, one can consider that the phase change occurs progressively in the two-phase region. This effect can be taken into account by defining an equivalent heat capacity of the underground in the heat equation, solved with a finite-element method. A more detailed description of the model is available in Ref. [6] and will be reminded in Section 2.

Different models are available to predict the performances of geothermal helical heat exchangers. The simplest model involves linear power source. This model does not take into account the soil inside the exchangers, and is not adapted to predict short duration heat solicitations due to the heat pump [11]. 3D models are too time consuming to enable simulations over long time period – typically annual performances of the exchangers over 1 year [8]. 2D axisymmetric such as horizontal rings model or annular cylindrical conduit model offer a good compromise between calculation duration and accuracy of simulations. They have been used to study heat storage in arid zones [12,13] or the heating and cooling of buildings taking into account the freezing of the subsoil [8]. Ref. [6] points out that the “annular cylindrical conduit” was easier to use and quite reliable. Moreover, thermal results taking into account the freezing of ground water appeared satisfactory. However, several questions remained. This paper investigates these points, using the models described in Ref. [6]. The thermal needs of a low-energy building over a year are used as boundary conditions, and the results from the “horizontal rings” model are compared in part 3.1.

2. 2D-axisymmetric models

2.1. Underground

The underground is considered as a semi-infinite solid, spatially homogeneous, with thermal transfers occurring by conduction. Its yearly temperature matches the heat equation, with an upper boundary condition corresponding to a sinusoidal variation of the upper temperature with a 1-year period: