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Investigations on the influence of aquifers on the ground temperature in ground-source heat pump operation

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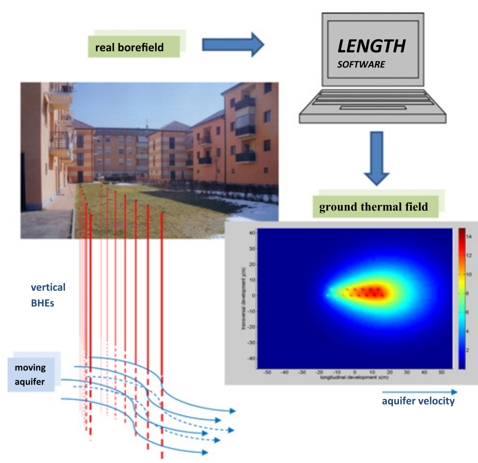
HIGHLIGHTS

- ▶ A moving aquifer opposes the thermal drift involved by ground-source heat pumps.
- ▶ A model of the influence of the groundwater flow on the thermal drift was set up.
- ▶ A 4-zone formulation was identified for the analytical model solution.
- ▶ An application of the model is done on contiguous borefields of existing buildings.
- ▶ Saving were evaluated on costs of investments (up to 16%) or operation (up to 6%).

GRAPHICAL ABSTRACT



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ABSTRACT

The winter operation of ground-source heat pumps is expected to lead to temperature decrease in the zones surrounding the vertical ground heat exchangers. The following thermal drift phenomenon occurring over the years is still deeply studied from both the experimental and the theoretical viewpoint.

A moving aquifer tends to oppose the thermal drift, due to the advection groundwater phenomena. For this purpose, a modelling study on the quantitative influence of the groundwater flow on the thermal drift is performed. Then, the analytical solution of the moving infinite line source is applied. Different forms (closed analytical, asymptotical or tabled one) are identified for this solution depending on the value range of the thermal physical parameters of the system.

Referring to a particularly critical case study, an easy-to-use application of the model based on this analytical solution is then presented. An evaluation is carried out as well on the interaction between the existing borefield and a nearby one, being operated afterwards, in presence of either still or moving aquifer.

Finally, the influence of the actually existing flow upon improving the effective operating conditions of the heat pump plant is assessed. Moreover, when groundwater flow is taken into account, the decrease of the total borehole length is evaluated.

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Nomenclature

Latin symbols

B	borehole spacing (m)
BHE	borehole heat exchanger
c	ground specific heat (J/(kg K))
C	costs (€)
COP	heat pump coefficient of performance
E	energy (kW h)
Fo	Fourier number $(a_{eff} \cdot tr_{bore}^2)$
h	equivalent operation hours
H	borehole depth (m)
i	hydraulic gradient (m)
K	hydraulic conductivity (m/m)
L	total exchange length (m)
M	coefficient of proportionality between SCOP and Carnot efficiency (−)
NB	borehole number
P	power (W)
Pe	Péclet number $(U_{eff} \cdot r_{bore}/a_{eff})$
Q	heat exchange rate (W)
q	specific heat exchange rate (W/m)
r	radius (m)
$\bar{r}$	dimensionless radius (r/r_{bore})
SCOP	seasonal COP
T	temperature (°C)
t	time (s)
U	seepage velocity (m/s)

Greek symbols

α	ground thermal diffusivity (m^2/s)
β	angle (radiant)
Δ	variation operation of the following quantity
λ	ground thermal conductivity (W/(m K))
v	Darcy velocity (specific discharge) (ϕU) (m/s)
ρ	density (kg/m^3)
ϕ	porosity (−)

Subscripts

b	building
$bore$	referred to borehole wall
$cool$	referred to heat pump evaporation temperature
e	electric, equivalent
eff	effective
f	fluid
g	ground
hot	referred to heat pump condensing temperature
Max	maximum
ma	moving aquifer
o	operation
p	plant, penalty
s	solid
sa	still aquifer
0	initial

1. Introduction

The ground-source heat pump (GSHP) systems can provide high energy efficiency for space heating and cooling.

Some general reviews [1–5] underlined the relevance of the low enthalpy resources and ground-source heat pump applications. The thermal performance of GSHP systems clearly also depends on the thermal quality of the building envelope and the ambient air temperature, as analyzed by Kharseh and Altorkmany [6].

It is well known that the thermal behaviour of these systems has to be investigated on the long term, i.e. over multiannual time horizons. This aspect was deemed crucial in the perspective of a long-lived and efficient operation of the designed plants. In addition, this technology persistently calls for control of the high investment costs which persistently are involved.

The most common solution is the *closed loop* system with vertically oriented borehole heat exchangers (BHEs), since they allow small land area requirements. The design of this system is an essential stage: if the total length of the ground heat exchangers is underestimated, the energy efficiency of the heat pump will be damaged; if on the other hand it is overestimated, the initial cost of the plant system unnecessarily increases. For this purpose, it is very important to consider the presence of the groundwater flow, since it represents a magnifying factor of the heat transfer process, due to the advective component in addition to the already existing conductive one.

Most design tools neglect the effect of the aquifer motion in the heat transfer, as its contribution is generally taken into account by means of an equivalent thermal conductivity of the ground. However, this assumption can be acceptable only for low velocity of the aquifer. Chiasson et al. [7] carried out a study to analyse the effects of the groundwater flow on the heat transfer of vertical closed loop heat exchangers by means of a finite element method. They analysed the performance of a single borehole and of a 4×4 borefield and they concluded that the simplified approaches neglecting aquifer motion usually bring about overdesign of the borefield.

In literature, theoretical research contributions were then proposed on this specific subject, which focused analytical and numerical approaches. The most diffused analytical methods derive from the moving infinite line source model [8] which describes the thermal field of a uniform medium that moves through a fixed heat source. Sutton et al. [9] used the analytical and numerical approach making use of the new function introduced by Chaudry and Zubair [10] and termed *generalized incomplete gamma function* to describe the thermal field of the moving infinite line source. Diao et al. [11] studied the combined heat transfer of conduction and advection in the vertical ground heat exchangers by an analytical approach based on the moving infinite line source too. The analytical approach was also used by [12–14]. Molina-Giraldo et al. [15] pointed out an analytical solution of a model based on the moving finite line source, which allows the edge thermal effects of the vertical heat exchanger to be considered. This approach aims at hindering an actual drawback of the infinite line source model, which is unable to account for any axial effects. Zhang et al. [16] making use of the analytical approach investigated the thermal performance of pile foundation heat exchangers, well known as “energy piles”. In their analysis, the heat conduction and the advection were included and the authors concluded that the effect of the groundwater should not be negligible.

Another kind of analytical methods derives from processing and direct solution of the “native” conservation equations written in an axial-symmetric geometry. An example of this approach is available in [17], though its implementation was found to involve some difficulties in obtaining the solution of the model equations.

Numerical methods consider less simplified models and pursue the solution by means of a variety of approaches based on the solution of a system of discretised equations. The literature is very rich of successful examples of these applications. Fan et al. [18] solved the energy equation, describing the non-isothermal groundwater flow in a saturated porous medium, by an in-house developed Finite Volume Method adopting an unstructured mesh. Carotenuto