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A new RC and g-function hybrid model to simulate vertical ground heat exchangers

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ABSTRACT

This paper presents a new hybrid two-dimensional model to simulate single U-tube ground heat exchangers based on the use of the electrical analogy to model heat transfer within the borehole and thermal response factors (short and long time-step g-functions) to estimate heat flow to the surrounding ground. Unlike other similar models, heat transfer equations are discretized only within the borehole domain, with two nodes for the fluid and two additional nodes for the grouting material, reducing the number of equations as ground temperature nodes are not considered. The substitution of ground nodes with short and long-term g-functions allows the simulation with short time steps keeping the possibility of simulating periods of several years. A complete analysis of the influence of characteristic parameters of the model in terms of the heat conduction path, vertical discretization level and equivalent heat capacity, has been carried out. The model shows a good performance for short simulation time-steps of five minutes for the prediction of both the short-term and long-term response. It has been successfully validated through comparison with a numerical computational fluid dynamic (CFD) reference model, achieving good RMSE values, which were smaller than 0.15 °C for water outlet temperature and borehole surface mean temperature.

1. Introduction

According to a recent report prepared by the U.S. Energy Information Administration (IEA), building sector, which is divided between residential and commercial end users, accounts for nearly one quarter of the total delivered energy consumed worldwide [1]. Furthermore, as reported in the IEO2013 Reference case, total world energy consumption in buildings will experience an average annual growth rate of 1.6 percent per year. Space heating (37%), space cooling (10%), water heating (12%) and lighting (9%) reach almost 70% of building energy consumption [2].

In this context, many countries (U.S., European Union, etc.) have recommended or introduced appropriate measures for the integration of Renewable Energy (RE) technologies, such as the ground source heat pump (GSHP) systems, in the building sector [3,4]. Thus, in the European Union, by the end of 2014, a minimum amount of energy from RES in new buildings and in existing buildings subjected to major renovation will be compulsory, especially RE technologies that achieve a significant reduction in energy consumption like heating and cooling systems [5].

The use of the ground as a heat source or sink for heat pumps for space heating and cooling in commercial and residential buildings has become frequent, due to consequent better energy efficiency and lower carbon dioxide emissions if compared with conventional systems [6,7].

Because the ground temperature is generally higher than ambient temperature GSHP systems can achieve higher coefficient of performance (COP) than that of air source heat pump (ASHP) systems. In summer, GSHP systems operate in the cooling mode and the ground is then used as a “heat sink”. The ground temperature is generally lower than the ambient temperature in summer, leading to high energy efficiency for space cooling. Additionally, the use of the soil as a heat source (or sink) reduces temperature differences between heat and cool sources, allowing higher performance ratios [8].

Efficiency of a GSHP system is measured by the coefficient of performance (COP), which can be defined as the ratio between heat

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Nomenclature

c_P	specific heat (J/kg K)
C	thermal capacitance (J/K)
d	pipe spacing (m)
Fo	Fourier number
g	non-dimensional response factor (g-function)
H	borehole depth (m)
h	convective heat transfer coefficient (W/m^2/K)
k	thermal conductivity (W/m/K)
l_b	effective conduction path
$\dot{m}$	fluid flow rate (kg/s)
q	heat flow rate (W)
R	thermal resistance (K/W)
r	radius (m)
t	time (s)
t_s	steady state time (s)
T	temperature (°C)

Greek symbols

α	thermal diffusivity (m^2/s)
β	grout volume ratio
Δt	discretization time-step (s)
ΔV	control volume (m^3)
Δz	layer thickness (m)
ρ	density (kg/m^3)
τ	minimum scale/limit time for long time-step g-function (s)

Subscripts

b	borehole
d	downward flow
f	fluid
fi	layer inlet fluid
fo	layer outlet fluid
g	grout
G	ground
p	pipe
u	upward flow
fp	fluid to pipe (heat convection)
gb	grout to borehole (heat conduction)
lt	long time-step
pi	inner surface pipe
pg	pipe to grout (heat conduction)
po	outer surface pipe
st	short time-step
inlet	inlet fluid
outlet	outlet fluid

Superscripts

i	layer index
j, k	time step indices

output and power input to drive refrigerant compressor and fluid pump. Heating COP typically ranges from 3.5 to 5 [9], despite the fact that greater cooling COP have also been reported [7]. Blum et al. [10] also reported that the use of GSHP systems in comparison to conventional heating systems may reduce CO_2 emissions between 15% and 77% depending on heat energy source and installation efficiency. Furthermore, ground heat exchangers can replace cooling towers avoiding potential health problems such as the 'Legionnaires' disease. Thus, GSHP have received an increasing interest in North America and in particular in the EU, where more than 720,000 units were installed at the end of 2007, representing a total electric or thermal power of 8758 MW [11].

GSHP systems have three main components: the ground side, where the borehole heat exchanger (BHE) is placed to exchange heat with the soil, the heat pump to convert that heat to a higher temperature level, and the building side, where useful thermal energy is added to (or extracted from) conditioned spaces.

An energy model for the whole system (ground, heat pump and building sides) is required to estimate the overall system COP. Thus, it is essential to have accurate but simple models for a fast and reliable simulation of the BHE. Heat transfer by borehole ground heat exchangers is still a challenge because it involves the analysis of short-time transient heat conduction in composite media together with sometimes complex geometric configurations. U-pipes grouted into vertical boreholes are likely the most common arrangement for BHE. Their design is critical to the long-term performance of the heat pump system and the application of dynamic models is required to capture the transient heat transfer. Typically, the main output of the BHE thermal analysis is the outlet water temperature under different operating conditions.

Analytical, numerical and hybrid models have been developed to simulate ground heat exchangers. Detailed literature reviews on the subject have been carried out by Florides and Kalogirou [12] and Yang et al. [13].

Analytical models are based on a number of simplifying assumptions for the borehole, such as the equivalent-diameter assumption, and are applied to both the design of BHE and the analysis of on-site test data [14]. The *cylinder source model* [15] and further simplifications such as the *line source model* [16], calculate heat transfer from the borehole wall to the surrounding soil neglecting the borehole internal region. However, short-time temperature responses heavily depend on this internal region (the heat capacities of fluid, pipe wall and grout), which can delay and damp the fluctuation of temperature. Then, neglecting the borehole internal region may cause some errors in determining thermal responses of GHEs and it cannot be applied to ground channels of other forms [17]. Recent new analytical models, such as the one developed by Li and Lai [18], in which downward and upward channels of U-shaped tubes are approximated as line sources or sinks of heat in a composite medium, seems to improve the performance of the common line-source models for short-time predictions. However, this two-dimensional model is not able to account for vertical ground properties variation.

Numerical models and totally discretized models [19,20] use finite difference or finite-volume methods to obtain the temperature distribution in the whole domain. This kind of models can obtain accurate results also on short time scales, but they usually require a great computational effort that limits their implementation within building simulation programs.

Other approaches, as those proposed by Eskilson [21] and later by Yavuzturk and Spitler [22], make use of dimensionless temperature response factors (g-functions) to estimate borehole surface temperature. These factors are computed with a two step process. First, an analytical and/or numerical approach of the borehole is developed to determine the response to a unit step function heat pulse. In the approach proposed by Eskilson [21], the borehole is approximated and simplified as a line-source of finite length. The capacitance of the individual borehole elements such as the pipe