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# Numerical and experimental validation of a new hybrid model for vertical ground heat exchangers

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ABSTRACT

A numerical and experimental validation of a new simplified model to simulate single U-tube ground heat exchangers is presented in this paper. The model is 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. 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. The model has been validated experimentally by using the reference data sets drawn from two tests (constant heat input rate and interrupted tests) made under controlled laboratory conditions. The results have also been compared with the simulated data from a detailed Computational Fluid Dynamics model of the experimental system. A very good agreement has been observed for the modeled outlet fluid and borehole temperatures, with root mean square and relative error values smaller than 0.2 °C and 0.3%, respectively.

## 1. Introduction

Building sector accounts for nearly one quarter of the total delivered energy consumed worldwide [1] and, as reported in the IEO2013 Reference case, total world energy consumption in buildings (70% of which is due to space heating, space cooling, water heating and lighting) will experience an average annual growth rate of 1.6% per year. In this context, many countries 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. Thus, Kaufmann et al. [2], who give a summary of the issues associated with a renewable energy requirement in the model energy building codes in the US, consider that GSHPs are high efficiency systems which provide an alternative to photovoltaic systems. On the other hand, European Union Directive 2009/28/EC [3] encourages the use of measures that set minimum requirements for the use of energy from renewable sources in a Community context and the use of more energy-efficient applications through building regulations and codes.

GSHP systems have three main components: the ground side where the borehole heat exchanger (BHE) is placed and that is used to get heat out of or into the ground, the heat pump to convert that heat to a suitable temperature level, and the building side transferring the heat or cold into the rooms. A heat pump is used in winter to extract heat from the relatively warmer ground and pump it into the conditioned space. The process may be reversed in summer, extracting the heat from the conditioned space and sending it out to a ground heat exchanger that warms the relatively cool ground [4]. Due to the high thermal inertia of the soil, ground temperature below a certain depth remains nearly constant throughout the year. Thus, the earth offers a nearly steady and large heat source, heat sink and heat storage medium for thermal energy uses while air temperature is affected by higher climatic variations. More importantly, the use of the soil as a heat source or sink decreases the difference between the reservoir temperatures, getting higher efficiencies.

There is a vast number of applications of GSHP systems. Balbay and Esen [5] present a feasibility study to use a GSHP system for snow melting on pavements and bridge decks in Turkey. Esen and Yuksel [6] also show the use of GSHP with a spiral BHE in a standalone greenhouse heating system. Among the most recent works, it is worth to highlight the one developed by De Carli et al. [7] which is focused on the energy performance of direct expansion GSHP systems with BHEs in heating mode at residential building installations.

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

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**Nomenclature**

| | |
|---|---|
| $c$ | specific heat (J/(kg K)) |
| $C$ | thermal capacitance (J/K) |
| $d$ | spacing between pipes (m) |
| $f$ | friction factor |
| 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)) |
| $l$ | effective conduction path |
| $L$ | pipe length (m) |
| $\dot{m}$ | fluid flow rate (kg/s) |
| $Nu$ | Nusselt number |
| $Pr$ | Prandtl number |
| $Q$ | heat flux (W) |
| $R$ | thermal resistance (K/W) |
| $r$ | radius (m) |
| $Re$ | Reynolds number |
| $t$ | time (s) |
| $t_s$ | time scale |
| $T$ | temperature (K) |
| $V$ | volume (m$^3$) |
| $x$ | non-dimensional variable equal to $\ln(t/t_s)$ |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | thermal diffusivity (m$^2$/s) |
| $\beta$ | non-dimensional factor |
| $\Delta t$ | discretization time step (s) |
| $\tau$ | limiting time scale (s) |
| $\rho$ | density (kg/m$^3$) |

*Subscripts*

| | |
|---|---|
| $b$ | borehole |
| $f$ | fluid |
| $g$ | grout |
| $G$ | ground |
| $in$ | inflow index |
| $p$ | pipe |
| $P$ | pressure |

*Superscripts*

| | |
|---|---|
| $i$ | time step index |
| $k$ | time step index |

the useful heat output and the electric power input used to drive the compressor and pump for the ground loop. The heating COPs typically range from 3.5 to 5 [8] while greater cooling COPs have also been reported [9]. Furthermore, ground heat exchanger can substitute the refrigeration towers avoiding problems related to legionellosis. Blum et al. [10] also reported that the use of GSHP systems in comparison to conventional heating systems leaded to $CO_2$ savings between 15% and 77% depending on the supplied energy for the heat pumps and the efficiency of installation. Thus, GSHP have received an increasing interest in North America and also in the EU, being one of top regions in the development of this kind of technology, with more than 720,000 units at the end of 2007 and an installed power of 8758 Mw [11].

Some authors [12] have stated that the economic profit of GSHP systems in mild climates, which are mainly used as HP, is more difficult to achieve than in cold climates. However, greenhouse gas emission reduction is significantly larger than in cold climates.

A simultaneous modeling of the whole system (ground side, heat pump and building site) is required to estimate the COP of the overall system. Thus, for a fast and reliable simulation of the system, it is essential to have sufficiently accurate and computationally cheap simulation models of the BHE.

The BHE usually consists of a closed loop or coaxial pipes lowered into a borehole. Pipes in a ‘U’ loop and grouted into vertical boreholes are likely the most common form of BHEs. 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 heat transfer inside and outside the borehole. This heat transfer process must be treated on the whole as a transient process. Generally, the main objective of the BHE thermal analysis is to determine the temperature of the heat carrier circulating fluid under different operation conditions.

A myriad of models have been developed in order to simulate ground heat exchangers: analytical, numerical and hybrid models [13]. Florides and Kalogirou [4] present various types of ground heat exchangers and the evolution and description of the different models used in the literature to simulate the heat transfer process. Yang et al. [14] give a detailed literature review of the vertical GSHP systems and also explain the most typical simulation models of the vertical ground heat exchangers. More specifically, a complete analysis and comparison of different methods used to evaluate the borehole thermal resistance, which plays an important role in the heat transfer from the fluid to the ground, are developed by Lamarche et al. [15].

Analytical models are based on a number of simplifying assumptions of the borehole and are applied to the design of BHEs, the analysis of in-situ test data and also to evaluate the thermal effect of a multiple BHE on the surrounding soil [16]. The cylinder source model [17] and further simplifications, such as the line source model [18] use heat transfer theory of these sources (or sinks) to solve for the heat transfer rate from the borehole wall to the surrounding soil neglecting the internal region of the borehole. Nevertheless, 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 BHEs and it cannot be applied to ground channels of other forms [19]. Recent new analytical models, such as the one developed by Li and Lai [20], 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 variation of ground properties.

Numerical models and totally discretized models use finite difference, finite element or finite-volume methods to solve the temperature distribution in the whole domain. Bauer et al. [21] developed two-dimensional finite difference models for different types of BHE. Al Khoury et al. [22] introduced two finite elements for geothermal heating systems in order to simulate coupled steady state heat and groundwater flow. In their second work [23] the authors presented an extension of the former model for transient state. He et al. [24] developed a dynamic three-dimensional BHE numerical model based on finite volume elements to simulate the dynamic response of the circulating fluid