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Numerical modeling of ground thermal response with borehole heat exchangers connected in parallel

Patricia Monzó[a,*], Anjan Rao Puttige[a], José Acuña[a], Palne Mogensen[a], Antonio Cazorla[b], Juan Rodriguez[c], Carla Montagud[b], Fernando Cerdeira[d]

[a] KTH Royal Institute of Technology, Brinellvägen 68, Stockholm 100 44, Sweden
[b] IUIIE - Instituto Universitario de Investigación en Ingeniería Energética, Universitat Politècnica de València, Camino de Vera s/n, Valencia 46022, Spain
[c] EnergyLab, Fonte das Abelleiras s/n, Campus Universidad de Vigo, Vigo 36310, Spain
[d] Universidad de Vigo, Maxwell 16, Vigo 36310, Spain

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ABSTRACT

With bore fields for energy extraction and injection, it is often necessary to predict the temperature response to heat loads for many years ahead. Mathematical methods, both analytical and numerical, with different degrees of sophistication, are employed. Often the g-function concept is used, in which the borehole wall is assumed to have a uniform temperature and the heat injected is constant over time. Due to the unavoidable thermal resistance between the borehole wall and the circulating fluid and with varying heat flux along the boreholes, the concept of uniform borehole wall temperature is violated, which distorts heat flow distribution between boreholes. This aspect has often been disregarded. This paper describes improvements applied to a previous numerical model approach. Improvements aim at taking into account the effect of thermal resistance between the fluid and the borehole wall. The model employs a highly conductive material (HCM) embedded in the boreholes and connected to an HCM bar above the ground surface. The small temperature difference occurring within the HCM allows the ground to naturally control the conditions at the wall of all boreholes and the heat flow distribution to the boreholes. The thermal resistance between the fluid and the borehole wall is taken into account in the model by inserting a thermally resistive layer at the borehole wall. Also, the borehole ends are given a hemispherical shape to reduce the fluctuations in the temperature gradients there. The improvements to the HCM model are reflected in a changed distribution of the heat flow to the different boreholes. Changes increase with the number of boreholes. The improvements to the HCM model are further illustrated by predicting fluid temperatures for measured variable daily loads of two monitored GCHP installations. Predictions deviate from measured values with a mean absolute error within 1.1 and 1.6 K.

1. Introduction

A conventional ground-coupled heat pump (GCHP) system consists of three main components: an indoor air or water circuit in the building, an outdoor heat carrier fluid circuit buried in the ground, and a heat pump. The advantage of using the ground as a heat source or sink derives from the fact that the ground temperature is relatively stable, higher during winter and lower during summer, as compared to the temperature of the outdoor air. The outdoor circuit is commonly a bore field, made up of a closed-loop of vertical U-pipe heat exchangers buried in the ground, the ground heat exchangers (GHEs), normally connected in parallel. The outdoor circuit is designed to keep the inlet fluid temperature of the heat pump (outlet fluid temperature of the GHE) within specified operational limits as the ground supplies the intended energy demand of the building. To ensure a sustainable and high performance of the heat pump over the years, long-term prediction of the thermal response of the ground and the GHEs are required. Both numerical and analytical methods are utilized to predict the long-term response of the ground. Usually convective processes in the ground are disregarded because of their irregular nature and only thermal conduction is considered. The thermal conductivity of the ground is known from e.g. thermal response tests.

Abbreviations: BH, borehole; EED, earth energy designer; EHCM, enhanced highly conductive material; FDM, finite difference method; FEM, finite element method; FLS, finite line source; GCHP, ground-coupled heat pump; GHE, ground heat exchanger; GLHEPRO, ground loop heat exchanger professional; HCM, highly conductive material; MAE, mean absolute error; MBE, mean bias error; RMSE, root mean square error; SBM, superposition borehole model; TRF, Temperature response function; TRL, Thermally resistive layer.

* Corresponding author.
E-mail address: patricia.monzo@energy.kth.se (P. Monzó).

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Nomenclature

α	Thermal diffusivity (m^2/s)
B	Borehole spacing (m)
D	Inactive upper part of the borehole (m)
δ	Thickness of the thermally resistive layer (m)
Fo_H	Fourier number, with H as the characteristic length
H	Total active borehole length (m)
k	Thermal conductivity (W/(m-K))
Q	Heat flow (W)
$\bar{Q}$	Average heat flow (W) per borehole
q	Heat flow per unit length (W/m)
$\bar{q}$	Average heat flow per unit length (W/m) per borehole
R_b	Local GHE thermal resistance ((m-K)/W)
R_b*	Effective GHE thermal resistance ((m-K)/W)
r_b	Borehole radius (m)
t	Time (s)
t_S	$H^2/9\alpha$ (s) Characteristic time
T	Temperature (°C)

Subscripts

bh	Borehole
bw	Borehole wall
g	Undisturbed ground

When modeling GHEs connected in parallel, two simultaneous boundary conditions are usually applied: a uniform temperature at all borehole walls and a defined total heat flow to the bore field. The assumption of a uniform borehole wall temperature has its foundation on the parallel hydraulic connection of the boreholes and on the small temperature difference between incoming and outgoing heat carrier fluid. Because of the thermal resistance between the heat carrier fluid and the borehole wall and the fact that the heat flux increases towards the borehole ends (bottom and top), the condition at the borehole wall differs from the assumption of a uniform temperature along the borehole wall.

This paper describes improvements applied to the numerical approach reported in Monzó et al. [23] in order to correct the representation of the temperature and heat flux profiles at the borehole wall. The model presented in this paper is utilized to generate the long-term temperature response for multiple bore field configurations when a constant total heat flow is injected into the bore field. The long-term temperature response obtained from the model described in this paper is illustrated along with the long-term temperature response obtained from the previous version of the model and other state of the art solutions. The improved model is also utilized to compute daily fluid temperature predictions for variable measured daily loads of two monitored GCHP installations. The predicted daily fluid temperatures are compared with the corresponding measured fluid temperatures and with the predicted values obtained from the previous numerical model.

2. Background

The energy demand of a building is characterized by a variable (heating and/or cooling) load profile. Subsequently, if using a GCHP with vertical boreholes, a bore field is also subjected to a variable load profile (heat extraction and/or injection). Commercial design software programs widely in use, such as Earth Energy Designer (EED) [14] and Ground Loop Heat Exchanger Professional (GLHEPRO) [20], are capable of easily predicting the temperature response due to a variable load profile (repeated over the user's simulation time with a period of one year) for hundreds of bore field configurations, normally contained in their pre-calculated libraries. Due to the linear nature of heat conduction, the thermal response of the bore field to a variable load, the procedure implemented in these software programs, is based on a sequential superposition of the stepwise variable loads over the characteristic temperature response of the bore field, traditionally called the g-function.

The g-function is a dimensionless temperature response factor that relates the change in temperature over time at the borehole wall (T_{bw}) from its undisturbed value (T_g) when a constant total heat load ($\bar{q} \times$ H) is injected into the bore field. This response is obtained from the assumption that pure heat conduction occurs in a homogenous surrounding ground medium with the definition of constant temperature (undisturbed value) at the boundaries of the surrounding ground. The g-function is usually represented over a non-dimensional time and is unique for given geometrical aspect ratios of the borehole field. The g-function is mathematically defined in Eq. (1)

$$T_{bw} - T_g = \frac{\bar{q}}{2\pi k} g\left(\frac{t}{t_s}, \frac{r_b}{H}, \frac{B}{H}, \frac{D}{H}\right) \quad (1)$$

One important aspect of the g-function generation is the definition of the boundary condition at the borehole wall as discussed in Bernier [2]. Eskilson [10] introduced the concept of the g-function, in which the definition of the boundary condition at the borehole wall was carefully studied. Three types of boundary conditions at the borehole wall were considered and implemented in Eskilson's 3D-finite difference method (FDM) computing program (SBM-Superposition Borehole Model). Cimmino and Bernier [6] provided a comprehensive categorization of these different types of boundary conditions. The first boundary condition assumes an equal heat distribution among the boreholes and a uniform heat flux along their depth. The second boundary condition refers to an average borehole wall temperature in all the boreholes. In this second type of boundary condition the heat extraction rate is different in each borehole but it is uniformly distributed along each borehole depth. The third type of boundary condition considers that the temperature along the borehole walls is uniform and equal in all boreholes. Simultaneously, the total heat flow in all the boreholes should be equal to the total heat flow transferred to the bore field at any given time, which should be constant for the g-function generation. This third boundary condition was Eskilson's preference for the g-function generation.

The assumption of a uniform temperature along the borehole length can be justified with the small temperature difference between incoming and outgoing heat carrier fluid in U-pipe GHEs at high flow rates [16]. The second assumption, the same borehole wall temperature in all boreholes, is justified by the hydraulic and thermal connections that occur when boreholes are connected in parallel. The uniform borehole wall temperature condition is widely accepted as a good representation of the thermal process at the borehole wall. Therefore, g-functions were generated for several bore field configurations and implemented in libraries of commercial design tools. Since then, these temperature response factors by Eskilson have been considered as benchmark solutions.

During the last two decades, exhaustive research activities have been dedicated to analytical solutions for the g-functions because of their flexibility, especially in design and optimization tasks. The efforts have been focused on finding accurate and fast computational methods for the generation of g-functions. Early efforts were dedicated to making the analytical solution practical for engineering purposes. In this direction, simpler expressions of the FLS solution to calculate the mean borehole wall temperature were investigated by Eskilson [11], Zeng et al. [29], Lamarche and Beauchamp [17], and Claesson and Javed [8]. The simplifications proposed by Lamarche and Beauchamp [17] and Claesson and Javed [8] could