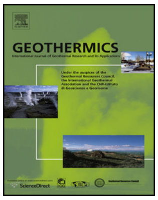
Geothermics 56 (2015) 35–44

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics



A novel numerical approach for imposing a temperature boundary condition at the borehole wall in borehole fields

Patricia Monzó[a,*], Palne Mogensen[a], José Acuña[a], Félix Ruiz-Calvo[b], Carla Montagud[b]

[a] *Energy Technology Department, KTH Royal Institute of Technology, Brinellvägen 68, 100 44 Stockholm, Sweden*
[b] *Instituto de Ingeniería Energética, Universitat Politécnica de Valéncia, Camino de vera s/n, 46022 Valencia, Spain*

ARTICLE INFO

Article history:
Received 28 July 2014
Accepted 3 March 2015
Available online 26 March 2015

Keywords:
Borehole
g-Function
Long-term performance
Uniform borehole temperature

ABSTRACT

The design of a borehole field should be based on a long-term simulation of its thermal response for the intended energy loads. A well-known method to evaluate the response is based on a pre-calculated dimensionless function, the *g*-function. When calculating *g*-functions, there are two commonly used approaches for treating the boundary condition at the borehole wall: a constant heat flux at every instant of time, or a uniform temperature at a constant total heat flow to the borehole field. This paper is focused on a new approach to model the thermal process of borehole fields; in particular with a precise representation of a uniform temperature boundary condition at the borehole wall. The main purpose of this model is to be used as a research tool to either generate *g*-functions for particular cases or handle situations that cannot be addressed by others methods. First, the almost constant temperature along the borehole heat exchanger in operation requires a boundary condition of essentially isothermal boreholes along the depth. In a common case, the borehole heat exchangers are connected in parallel, thus all boreholes should have the same temperature. Also, the total heat flow to the borehole field should be constant over time. For this purpose, a numerical model in which the boreholes are filled with a hypothetical highly conductive material has been built, reproducing the isothermal condition. By thermally interconnecting the boreholes, the equal temperature condition is satisfied. Finally, the specified total heat flow is fed into one spot at the highly conductive material. The model is validated by generating *g*-functions of some simple borehole field configurations. The *g*-functions present, in general, a good agreement with the existing solutions for a similar boundary condition. Moreover, the model is also tested against real experimental data from a 2 × 3 borehole field at an office building. The simulated daily fluid temperatures are compared with measured daily fluid temperatures for the sixth year of operation. The simulated values present, in general, a good agreement with the measured data. The results show that there are no significant differences with regard to the boundary conditions at the borehole wall, which for this specific case is due to the fact that the system is thermally balanced.

1. Introduction

During the last years, ground-source heat pump (GSHP) systems have become increasingly popular among the renewable technologies due to their high efficiency and their contribution to the mitigation of CO_2 emissions. The most common GSHP systems in Sweden are those coupled to (nearly) vertical borehole heat exchangers (BHEs), the so-called ground-coupled heat pump (GCHP). In year 2012 there were a total of about 425,000 small (family houses) GCHP systems in Sweden, and 400 large borehole thermal energy storage (BTES) installations. While the growth rate of new small systems has slowed down, larger GSHP installations are nowadays starting to take a significant role in the Swedish low temperature heating energy supply (Andersson and Bjelm, 2013).

GCHP systems are mainly based on an energy exchange from the building to the ground, or vice versa. A heat pump normally connects the indoor circuit of a building with the outdoor circuit on the ground side. The heat pump performance depends among other things on a proper design of the outdoor circuit, which commonly consists of a set of vertical heat exchangers buried in the ground. The design of large BHE fields should account for extrinsic factors such as a realistic assessment of the heating and cooling demand of the building, the temperature limitations on the fluids at the hot and cold side of the heat pump (HP), and the available drilling area. Moreover, intrinsic factors such as the thermal properties of the ground and the possible presence of groundwater flow should be

---

[*] Corresponding author. Tel.: +46 8 790 7450.
E-mail address: patricia.monzo@energy.kth.se (P. Monzó).

http://dx.doi.org/10.1016/j.geothermics.2015.03.003
0375-6505/

Nomenclature

α	thermal diffusivity (m^2/s)
B	borehole spacing (m)
D	inactive upper part of the borehole (m)
Fo_H	$\alpha t/H^2$ (1) Fourier number, characteristic length H
H	active borehole length (m)
k	thermal conductivity (W/m K)
Q	total heat flow (W)
q	heat flow per unit length of borehole (W/m)
r_b	borehole radius (m)
t	time (s)
t_s	$H^2/9\alpha$ (s) characteristic time
T	temperature (°C)

Abbreviations

BC	boundary condition
BH	borehole
BHE	borehole heat exchanger
BTES	borehole thermal energy storage
EED	earth energy designer software
FDM	finite difference method
FEM	finite element method
FLS	finite line source
GCHP	ground-coupled heat pump
GLHEPRO	professional ground loop heat exchanger software
GSHP	ground-source heat pump
HCM	highly conductive material
SBM	superposition borehole model
UPV	Universitat Politècnica de València

Subscripts

b	borehole
bw	borehole wall
g	undisturbed

evaluated. Taking all these factors into account, the design results in a borehole (BH) field with a particular arrangement that comprises a certain number of BHs of prescribed lengths. A common procedure for analyzing the thermal response of a BH field is to use temperature response factors, so-called *g*-functions. The concept of the *g*-function was first presented in Eskilson (1986,1987). The *g*-function is a thermal response factor for a specific geometry that relates the change of temperature at the BH wall, $T_b(t)$, over time with a constant average heat flow per unit BH length, q, imposed from time $t = 0$. Eq. (1) expresses the link between the *g*-function, the heat load, and the temperature, for a BH field installed in a ground with a thermal conductivity, k. T_g is the undisturbed ground temperature. Only heat conduction is considered.

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

The *g*-function is a function of dimensionless variables, r_b/H and B/H, representing the aspect ratios to the active BH length (H) of the BH radius (r_b) and BH spacing (B), respectively. The *g*-function depends also on a non-dimensional time t/t_s where t_s is a characteristic time defined as the Fourier number with H as the characteristic length and α as the thermal diffusivity of the ground, that is $Fo_H = \alpha t/H^2$. The upper inactive part, D, of the BH, which could be the part above the groundwater level or an insulated casing was dismissed by Eskilson as a negligible parameter in the *g*-function definition. As indicated previously, the main use of the *g*-function is in the simulation of the long-term thermal response of a BH field exposed to variable heat loads. It should be said that a straight-forward calculation of this response for a multi-BH field with variable loading conditions is normally not within the capability of the BH field designer. To simulate such a thermal response, a temporal superposition of variable loads is applied to the *g*-function, as mathematically expressed in Eq. (2). The variable load is split into n piecewise constant load steps q_i, starting at $t = 0$ with q_i lasting to t_1 where the next step q_2 starts and so on until the last step q_n ending at t_n. It should be noted that the geometrical aspect ratios have been omitted in the arguments of the *g*-function in Eq. (2).

$$T_{bw}(t) - T_g = \frac{1}{2\pi k} * \left(q_1 * g\left(\frac{t}{t_s}, , \right) - q_n * g\left(\frac{(t-t_n)}{t_s}, , \right) + \sum_{i=1}^{n-1} (q_{i+1} - q_i) * g\left(\frac{(t-t_i)}{t_s}, , \right)\right) \tag{2}$$

This procedure is applied in well-known commercial software programs such as earth energy designer (EED) (Hellström and Sanner, 1994) and GLHEPRO (Marshall and Spitler, 1994). When applying Eqs. (1) and (2), in BH design, it is important to note that there is a temperature drop between the circulating fluid and the BH wall related to heat transfer resistances in and around the BHE. A library of *g*-functions for many relatively simple BH field geometries is implemented in these software programs. However, these two software codes are limited when it comes to specifying irregular BH field geometries. Moreover, the users can neither impose variable monthly heat loads over different years, nor daily or hourly loads. Due to restrictions at available drilling sites, many real installations require specific and unique designs of BH field configurations, which are not implemented in the library of the above mentioned software. This paper presents a novel numerical model in which special attention is given to impose a uniform temperature boundary condition (BC) at the BH wall. It can e.g. be used as a research tool to generate *g*-functions or to simulate directly the thermal response (fluid temperature) of a BH field. Examples are cases that other methods cannot address such as spatially varying ground properties or imposing variable thermal loads. The model was first tested by generating *g*-functions for some simple BH fields, a single BH and a 2 × 3 BHs configuration, and compared with some reference solutions. Moreover, the model was also tested to simulate daily fluid temperatures, which were compared with experimental data. The model was set up according to the geometrical characteristics and ground thermal properties at the Demo site at the Universitat Politècnica de València (UPV), Spain. For this purpose, the model first generated the *g*-function corresponding to the UPV BH field; then, the simulated daily temperatures were obtained by imposing the measured heat loads to the model.

2. Background

The calculation of *g*-functions for multiple BH fields is a demanding and time consuming task. A variety of methods are in use, e.g. analytical, (semi)analytical and numerical, the latter based on finite difference (FDMs) and finite element methods (FEMs). A crucial point when generating *g*-functions is the BCs at the BH wall, which requires two simultaneous conditions to be fulfilled. Firstly, all BHEs should receive a uniform inlet fluid temperature (They are in general hydraulically connected in parallel, so that they are also thermally connected). Secondly, the total heat flow injected to the BH field must be constant for the *g*-function generation. The reference solutions assume that the walls of all BHs have a uniform temperature, but changing over time as the ground responds to the heat load. The total heat load must be constant over time, meaning