Energy & Buildings 172 (2018) 192–200

Contents lists available at ScienceDirect

Energy & Buildings

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

TRNSYS g-function generator using a simple boundary condition

Eui-Jong Kim

Department of Architectural Engineering, Inha University, Incheon 22212, Republic of Korea

A R T I C L E I N F O

Article history:
Received 28 March 2018
Accepted 5 May 2018
Available online 9 May 2018

Keywords:
Ground heat exchanger
Thermal response function
Finite line source model
Duct storage model
TRNSYS

A B S T R A C T

Ground thermal response functions, also well-known as *g*-functions, have been extensively used for sizing ground heat exchangers and performance analyses of ground coupled heat pump (GCHP) systems. A general approach used to generate *g*-functions is to define a wall boundary, e.g., uniform temperatures or uniform heat transfer rates. In this work, a TRNSYS *g*-function generator is proposed that uses the uniform heat transfer rates as a boundary to the finite line source (FLS) model. This boundary can be easily applied to the FLS model and the generating process is computationally rapid. The duct storage (DST) model—TRNSYS type 557—are used to test the proposed FLS-based *g*-function model. Results showed that the DST model was in good agreement with the proposed models but deviated with respect to the other boundary-based models. However, discussions on which the boundary is realistic are not yet completely concluded with this work since the DST model itself uses several simplifications.

1. Introduction

Ground-coupled heat pump (GCHP) systems have been increasingly used in recent years to attain higher energy efficiency compared to conventional, air-source heat pump systems. However, the system's drawback is that the installation of ground heat exchangers is costly [1,2], and some construction projects reject this solution at the early design phase [3]. Conversely, borehole heat exchangers (BHE), a common type of ground heat exchangers used in many countries, need a large borefield for installation to cover the required heating and cooling loads of a target building. In urban areas, the required installation space is not always affordable, and this can be a reason to reject potential usage of the GCHP systems during the design phase [3]. Since the underestimation in the sizes of BHEs causes an irreversible system failure, the current engineering methodologies used for sizing BHEs tend to overestimate their total lengths. An accurate sizing method may expand the installation of the GCHP systems.

The sizing of the BHEs is based on simulations where the BHE model is a key element of the process with given load data and parameters, such as the soil conductivity, heat pump performance, and BHE materials. The simulations must be executed for periods spanning several years since the ground temperatures gradually increase or decrease according to the load pattern until a quasi-steady-state condition is reached. A simulation period spanning 20 y is typically used for sizing purposes. Since the calculated total length of the BHEs under a predefined borefield configuration determines a required length per borehole that can be larger than an acceptable range in practice, time-consuming, iterative simulations are required to determine a final borefield configuration with a given unit length or vice versa [4–6].

A solution to this problem is to use ground thermal response functions that are employed in most of the commercial sizing tools, such as GLHEPro [7], EED [8], and GLD [9]. The thermal response functions can be predefined for typical borefield configurations, and thus a rapid evaluation of the maximum or minimum entering water temperatures (EWT) to heat pumps, which is the key design variable [10], can be calculated at specific conditions.

The thermal response function was first proposed by Eskilson [11]. In his work, two-dimensional (r, z) coarse numerical meshes for a single BHE case were used for simulations and the response functions for multiple BHEs were obtained using the spatial superposition method [12]. The function was given by tabulated data, and a number of datasets for typical borefield cases were provided. This was called a *g*-function, but other ground thermal response functions that have recently been developed using alternative methodologies are also customarily called *g*-functions. Monitoring the progress in the developments of detailed analytical models for BHE helps generate *g*-functions in a more convenient way. One popular analytical model is the finite line source model (FLS) [13]. The model can describe the axial heat transfer and the length H can thus be specified. Although this is derived for a single BHE case, the spatial superposition method can be applied to a borefield configured with several BHEs, thereby allowing expansion of the applicability of the FLS model. Several works with the FLS model have been carried out for GCHP simulations [14,15] and for generating *g*-functions [16–19]. The FLS model gen-

E-mail address: ejkim@inha.ac.kr

https://doi.org/10.1016/j.enbuild.2018.05.014
0378-7788/

Nomenclature

B	Borehole spacing (m)
BHE	Borehole heat exchanger
DST	Duct storage model
EWT	Entering water temperature to heat pumps (°C)
erfc	Complementary error function
F_o	Fourier number
FLS	Finite line source model
GCHP	Ground-coupled heat pump
H	Borehole length (m)
h_f	Convective heat transfer coefficient (W/m^2 °C)
HR	Hybrid reduced model
k_g	Ground thermal conductivity (W/m °C)
k_p	Pipe thermal conductivity (W/m °C)
LWT	Leaving water temperature from heat pumps (°C)
$\dot{M}$	Total mass flow rate (kg/s)
$\dot{m}$	Unit mass flow rate (kg/s)
N	Number of boreholes
Q	Total heat flux or ground load (W)
q	Heat transfer rate per unit length (W/m)
R_b	Borehole thermal resistance (m °C/W)
r	Radial direction or axis
r_b	Borehole radius (m)
$r_{p,i}$	Pipe inner radius (m)
$r_{p,o}$	Pipe outer radius (m)
$\overline{T_b}$	Average wall temperature (°C)
ΔT_b	Difference between $\overline{T_b}$ and T_g (°C)
T_g	Ground undisturbed temperature (°C)
T_f	Fluid temperature (°C)
$T_{f,in}$	= LWT, inlet fluid temperature (°C)
$T_{f,out}$	= EWT, outlet fluid temperature (°C)
t	Time (s)
t_g	$= H^2/9\alpha_g$, critical time (s)
z	Vertical direction or axis
α_g	Ground thermal diffusivity (m^2/s)
ρ	Density (kg/m^3)
c_p	Pipe specific heat (J/kg °C)
c_f	Fluid specific heat (J/kg °C)

erates the temporal variation of the average wall temperature of a BHE when a heat transfer rate is imposed, and thus, many FLS-based *g*-functions are obtained by inputting a heat transfer rate. This is the opposite condition to that pertaining to the Eskilson *g*-function that will be discussed in the following section. An attempt was expended to modify the boundary condition by imposing temperatures and observing the resulting heat transfer rates to match the FLS-based *g*-function with the Eskilson *g*-function. Such an effort was successful and both models were in good agreement [20]. However, differences exist among *g*-functions according to the different boundary conditions, particularly for cases with a large number of BHEs. A first detailed comparison between the boundaries was pursued by Cimmino and Bernier [20] that stimulated a debate on the issue based on detailed simulation and experimental tests [21,22]. However, this subject is still under debate.

The purpose of the work is not to identify which boundary is close to reality but to generate additional knowledge to contribute to this debate. The attempt aims to use an existing well-known numerical model to generate a *g*-function without resorting to predefined boundaries. These reference results will be used for comparisons with the original Eskilson *g*-function and a *g*-function generator proposed herein. The proposed generator uses the FLS model with a different boundary to that used by the Eskilson's *g*-function. This generator is implemented in TRNSYS [23] to use the resulting

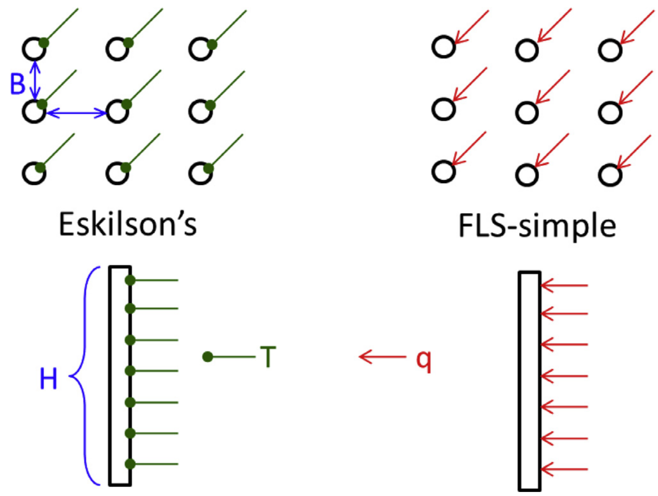

Fig. 1. Schematics of different boundary conditions used to generate *g*-functions (left: uniform temperature boundary, right: uniform heat transfer rate boundary).

g-function data in an existing TRNSYS BHE model that requires a thermal response function for simulation. Therefore, detailed comparisons among the models, and thus among the boundaries, can be accomplished based on TRNSYS simulations.

The following section summarizes the current boundary issue and the common methodology used to generate the response data. The generating process of the proposed *g*-function using the FLS model is then described, followed by the introduction of a proposed method to generate a *g*-function using a well-known BHE model that does not have to impose a wall boundary. This reference *g*-function will be used for comparison purposes. Simulation results and discussions are given in the Results section.

2. Review of the boundary conditions used for generating *g*-functions

To clarify the approaches employed in this work, the existing boundary conditions used for generating *g*-functions are briefly presented in this section. As mentioned earlier, differences in boundary conditions are first detailed in the work of Cimmino and Bernier [20]. In their work, three possible boundary conditions are presented, but two most commonly used boundary conditions are discussed in this work.

The first boundary requires that the borehole wall temperatures are equal for all the boreholes and are uniform along the length of the boreholes. This assumption is based on the fact that the leaving water temperatures (LWT) from the heat pumps are equal for all the boreholes when the parallel fluid circuit is used. The temperature differences between LWT and the entering water temperature (EWT) are small and in the order of 4–5°C, and the fluid temperatures are changed first along the downward leg of the U-tube and then along the other upward leg, thus resulting in similar average wall temperatures along the length.

Another boundary condition is that the heat transfer rates are equal for all the boreholes and are uniform along the length. Similar explanations to those provided for the first boundary condition can be used for this boundary, but result in *g*-functions that are distinct when a number of BHEs are considered for large time scales.

These boundaries are schematically shown in Fig. 1. The first boundary condition was also used in the Eskilson work to develop his well-known *g*-function, and the boundary is thus referred to as the Eskilson's *g*-function in this study. The second is referred to as the FLS-simple as it can be easily applied to the FLS model in a