Applied Thermal Engineering 103 (2016) 934–944

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Temperature response factors at different boundary conditions for modelling the single borehole heat exchanger

Antonella Priarone *, Marco Fossa

DIME, University of Genova, via Opera Pia 15a, 16145 Genova, Italy

HIGHLIGHTS

- Numerical model to calculate the Temperature Response Factors for a single BHE.
- Different BHE wall boundary conditions analyzed.
- Model able to consider the BHE position with respect to the ground surface.
- Obtained results provided in a tabulated form.
- Data useful for spatial and temporal superposition for *g*-function generation.

ARTICLE INFO

Article history:
Received 2 March 2016
Revised 7 April 2016
Accepted 8 April 2016
Available online 9 April 2016

Keywords:
Ground coupled heat pumps
Borehole heat exchanger design
Temperature response factors
g-functions

ABSTRACT

Design and simulation of borehole heat exchangers rely on the solution of the transient conduction equation. The typical approach for predicting the ground temperature variations in the short and long term is to recursively apply basic thermal response factors available as analytical functions or as pre-estimated tabulated values. In this paper a review of the existing response factor models for borehole heat exchangers (BHE) analysis is presented and a numerical model, built in Comsol environment is employed for calculating the temperature distribution in time and space around a single, finite length, vertical cylindrical heat source also taking into account its position with reference to the ground surface (effects of the adiabatic length or "buried depth" *D*). The temperature values are recast as dimensionless response factors in order to compare them with analytical solutions where available. Furthermore new temperature response factors suitable for describing the single Finite Cylindrical Source (FCS) under different operating modes (i.e. boundary conditions) are generated. Boundary conditions include imposed heat transfer rate, imposed temperature and a combination of both conditions, where spatially uniform temperature at the BHE interface is attained while also keeping constant the applied heat transfer rate.

1. Introduction

Ground coupled heat pumps (GCHP) are probably the most energy efficient solution for building space conditioning. This technology has encountered a wide diffusion in several cold climate countries, either in Northern Europe or North America where traditional air-to-air heat pumps cannot be efficiently employed for heating purposes at very low ambient (outdoor) air temperatures.

This technology can effectively concur to the attainment of the EU energy and climate targets. To promote a widespread exploitation of these resources on field and a large scale introduction of GCHP systems in both residential and institutional/commercial buildings, it is mandatory to define either technical guidelines for the correct sizing of ground heat exchanger fields or a set of regulatory and economic actions [1].

The most common solution for extracting or injecting heat from and to the ground is to bury closed loop heat exchangers either arranged near the ground surface or disposed vertically down to hundreds of meters (BHEs). If reliable drilling equipment is available, vertical heat exchangers are usually preferred to near horizontal or trench siblings due to the reduced requirement of land surface and to their capability of taking advantage of the stable and favorable temperatures of the deep soil. GCHP can cover a wide range of energy demand situations, from small residences to large commercial buildings. High efficiencies in such installations are related to the correct design of the borehole field in order to have suitable return temperatures of the heat carrier fluid for achieving high seasonal performance factors. Such a task can be accomplished through the correct modelling of the ground/

* Corresponding author.
E-mail address: a.priarone@unige.it (A. Priarone).

http://dx.doi.org/10.1016/j.applthermaleng.2016.04.038
1359-4311/

Nomenclature

B	radial distance from multiple sources (m)
c	specific heat (J/(kg K))
D	adiabatic depth (m)
erf	error function (–)
$erfc$	complementary error function (–)
E_1	exponential integral in ILS model (–)
F	Infinite Cylindrical Source (ICS) temperature transfer-function for imposed temperature (–)
Fo	Fourier number (–)
g	multi BHE temperature transfer function (–)
G	ICS temperature transfer-function for imposed heat flux (–)
H	active depth of the BHE (m)
J_0, J_1	Bessel functions of the first kind, of order 0 and 1 (–)
k	thermal conductivity (W/(m K))
$\vec{n}$	inward normal unit vector (–)
p	ratio r/r_b (–)
$\dot{Q}$	heat transfer rate (W)
r	radial coordinate (m)
T	temperature (K)
Y_0, Y_1	Bessel functions of the second kind, of order 0 and 1 (–)
z	vertical coordinate (m)

Greek letters

α	thermal diffusivity (m^2/s)
ρ	density (kg/m^3)
τ	time (s)
Γ	temperature transfer function (–)

Subscripts

ave	average
b	of the borehole, at borehole radius
gr	of the ground medium, of the ground domain
H	based on BHE active depth
p	r/r_b
Q	imposed heat flux
r	based on radius
sc	superconductive material
T	imposed temperature
∞	far field and initial condition

Superscripts

*	dimensionless
$\bar{}$	average along the depth H
$'$	per unit length

borefield system and suitable models are required to simulate the short to long time temperature evolution of the ground volume associated with the BHE field. From a thermal point of view, this volume can be very often considered as a purely conduction medium since ground water circulation (if present) is often confined in a thin layer compared to the vertical extension of the BHE volume. When meaningful underwater circulation is present a common approach is to include convection in the conduction equation (see for example [2] but often a pure conduction modelling, in terms of moving line sources, demonstrated to be able to efficiently describe the ground thermal behavior in presence of groundwater advection [3].

The borefield design goal is the definition of the best BHE geometry (BHE arrangement, their number and spacing) and the minimum overall length of vertical pipes with respect to the land availability and drilling equipment. The constraints of the problem and its starting information are the building heat loads in time, the ground thermal properties and the target seasonal heat pump performance.

In order to succeed in this design task, a number of solutions of the transient heat conduction equation have been proposed in order predict the ground temperature in time and space for given geometry and boundary conditions.

Carslaw and Jaeger [4] and Ingersoll et al. [5] first provided engineering models for evaluating the temperature evolution in the ground when a single heat source is active.

In both these early studies the borehole is modelled as an infinite length heat source. The most popular solutions for such a problem are the so called Infinite Line Source (ILS, Lord Kelvin, and later Ingersoll et al.) and Infinite Cylindrical Source (ICS, Carslaw and Jaeger). Both solutions allow the temperature distribution in the ground to be evaluated in terms of a temperature response factor (TRF) which is a function of the radius based Fourier number. ILS and ICS models were both solved for the constant heat flux boundary condition and the ICS for the imposed wall temperature too. Imposed heat rate cases result in similar trends for ILS and ICS models except for the early part of the temperature evolution. These two solutions can be proved to be in absolute agreement after a given dimensionless time is elapsed as also discussed in recent papers [6,7]. The ICS and ILS solutions at imposed heat rate encountered a great success in many engineering models, from short time analyses (TRT experiments, e.g. [8–11]) to long term simulations [12]. The ICS solution at imposed temperature, also known as the "F" function is rarely employed probably due to the fact that in practice this boundary condition is difficult to realize in real experiments or field equipment. Thanks to the work of the Lund research group (e.g. [13], the TRF approach was extended to the description of finite length (linear) heat sources (FLS). Lamarche and Beauchamp [14], after Zeng et al. [15], developed a new solution for the Finite Line Source model (FLS) in terms of semi analytical expressions to be numerically integrated. Bandos et al. [16] proposed new analytical and explicit expressions for calculating the ground temperature field induced by a finite line source. Fossa [17] and Fossa and Rolando [18] refined the Bandos expressions and proposed approximate fully analytical solutions for the FLS problem suitable for spatial and temporal superposition in very reduced computation times. Claesson and Javed [19] rearranged the mathematical development of the (semi analytical) FLS solution in a way able to provide new expression which greatly reduces the computation time of the response factor values.

One of the strength of the TRF approach is the possibility to exploit the linear properties of the conduction Fourier equation for superposing the base solution in space and hence to obtain new TRFs able to describe the ground response to a system of heat sources. These multiple source TRFs are usually referred as "g-functions" after the work of Eskilson [13]. The approach of the Lund group was to numerically calculate the temperature field from a single (finite) heat source either at imposed heat flux or imposed temperature. The code in charge to manage such a problem, discretizing the Fourier equation according to a finite difference scheme, was named SBM [20]; its g-functions are embedded in commercial codes for BHE field design as EED and GLHEPRO [21,22].

From the point of view of numerical approach, Zanchini and Lazzari [23] proposed a new method that considers also the inter-