Geothermics 70 (2017) 260–270

Contents lists available at ScienceDirect

Geothermics

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

Thermal resistance capacity model for short-term borehole heat exchanger simulation with non-stiff ordinary differential equations

A. Minaei, M. Maerefat*

Department of Mechanical Engineering, Tarbiat Modares University, P.O. Box 14115-143, Tehran, Iran

ARTICLE INFO

Keywords:
Ground source heat pump
Borehole heat exchanger
Thermal network
Short-time response
Non-stiff equations
STRCM

ABSTRACT

In the present study, a new thermal resistance capacity circuit for the heat transfer modeling in borehole heat exchanger with low computation time is developed. Generally, the thermal circuit models result in sets of ordinary differential equations which are solved numerically. The system of equations derived from the traditional thermal resistance capacity model (TRCM) are usually stiff and lead to unstable results unless for a very small time steps which can increase the computation time significantly. Meanwhile, the system of ordinary differential equations derived from the present model is non-stiff and there is no time step limitation for the stability of the results. It is shown that the present model yields accurate and stable results even for large time steps. Finally, the two-dimensional model is extended to the three-dimensional model. The results of the three-dimensional solution of the present model are in good agreement with the numerical results and experimental measurements reported in the literature.

1. Introduction

Using ground source heat pump (GSHP) systems for heating and cooling of the buildings has got increasing attention during the last several years. These systems offer higher energy efficiency and lower environmental impact for air-conditioning compared to the conventional air conditioning systems. These systems mainly consist of a conventional heat pump coupled with a ground heat exchanger (GHE). The GHE acts as a heat source for heating and as a heat sink for cooling. Vertical borehole heat exchangers (BHE) with U- pipes installed inside boreholes are the most common types of the ground heat exchangers. In these heat exchangers, a working fluid passes through the U-pipes and the borehole is filled with grout.

Several analytical methods, numerical methods and combination of both the methods are introduced in the related literature focusing the modeling heat transfer in the BHEs.

The infinite line source (ILS) model (Ingersoll and Plass, 1948) and infinite cylindrical source (ICS) model (Carslaw and Jaeger, 1947) are the most common solutions among the analytical models. In both the ILS and ICS models the borehole is assumed as a linear and cylindrical heat source of infinite length surrounded by an infinite homogeneous medium and the heat transfer is considered just in the radial direction. An analytical solution with a finite line source (FLS) is proposed by Zeng et al. (2002), where the borehole is considered as a finite length problem with heat transfer in both the radial and axial directions.

Eskilson (1987) introduced the concept of the G-functions, which is defined as a temperature response of the borehole to unit step pulse heat flux imposed on the borehole wall in a two-dimensional axial-radial coordinate system. The G-function is calculated through a hybrid numerical-analytical method.

In all the above-mentioned methods, the thermal capacities of the fluid, the pipe and the grout are not considered. Therefore, they are not appropriate for short time periods.

Yavuzturk (1999) is one of the pioneer researchers who studied the short-time behavior of the BHEs. He developed a numerical method to compute the short time step G-function. The thermal capacity influence of the grout is considered, but those of the fluid and the pipe are not.

There are some short time step analytical solutions proposed by Lamarche and Beauchamp (2007), Bandyopadhyay et al. (2008) and Javed (2011), in which the real geometry of a borehole is simplified as a single cylinder with equivalent diameter. This assumption simplifies the complex heat transfer phenomenon inside the borehole. The effects of some critical parameters such as shank spacing are not included in the solution. Li and Lai (2013) proposed the infinite composite-medium line-source model, where each pipe is assumed as a line source of infinite length. In their model, the heat capacity of the circulating fluid and the pipe material are not included in the solution.

Direct three-dimensional numerical solutions, (e.g. finite difference, finite volume and finite element) have been applied to develop 3D models where the flow inside of the borehole and the overall bore field

* Corresponding author.
E-mail address: maerefat@modares.ac.ir (M. Maerefat).

http://dx.doi.org/10.1016/j.geothermics.2017.06.011
Received 25 October 2016; Received in revised form 5 May 2017; Accepted 22 June 2017
0375-6505/

Nomenclature

A	Area (m^2)
c_P	Specific heat ($Jkg^{-1}k^{-1}$)
C	Thermal capacitance ($J k^{-1}$)
G	Non-dimensional response factor (g-function)
H	Borehole depth (m)
h	Convective heat transfer coefficient ($Wm^{-2}K^{-1}$)
k	Thermal conductivity($Wm^{-1}K^{-1}$)
$\dot{m}$	Mass flow rate (kgs^{-1})
Q	Heat supply (W)
q	Heat supply for unit length (Wm^{-1})
R	Thermal resistance ($W^{-1}m K$)
r	Radius (cm)
T	Temperature (°C)
t	Time (min)
x	the location of the grout center of mass in TRCM
x_c	Half distance between centers of U-tube pipes (cm)

Greek symbols

α	Thermal diffusivity ($m^2 s^{-1}$)
Δt	Discretization time-step (s)
Δz	Height of the vertical slice (m)
μ	Dynamic viscosity ($kg m^{-1} s^{-1}$)
λ	Eigenvalue
ρ	Density ($kg m^{-3}$)

Subscripts

b	Borehole
D	Downward flow
f	Fluid
f1	Fluid in supply pipe
f2	Fluid in return pipe
ff	Fluid to fluid
fg	Fluid to grout
g	Grout
gb	Grout to borehole wall
gg	Grout to grout
ground	Ground far from the borehole
inlet	Inlet fluid
j	Slice index
outlet	Outlet fluid
p	Pipe
pi	Inner surface of u-tube
po	Outer surface of u-tube
s	Soil
U	Upward flow

Superscript

i,n	Time step indices

have been considered at the same time. Some of the Noteworthy numerical methods include the studies by Li and Zheng (2009), Marcotte and Pasquier (2008), Nabi and Al-Khoury (2012a, 2012b), Rees and He (2013), and Heidarinejad et al. (2010). The full numerical methods are not appropriate for implementation in building energy simulation software and simplified methods are necessary.

In the recent years, the thermal network-based methods have attracted a major concern. These models are based on the analogy between thermal and electrical conduction. Many researchers proposed this approach to simulate the heat transfer in the borehole and its surrounding vicinity. De Carli et al. (2010) proposed the Capacity Resistance (CaRM) Model for various BHE configurations to simulate the heat transfer between the ground and the borehole, where a steady state heat transfer has been considered inside the borehole. Zarrella et al. (2011) improved the CaRM model for a double U-pipe BHE by considering the transient heat transfer inside the borehole through the addition of two supplemental capacity nodes to the grout. In their work, the grout is divided into two parts: the core and the shell, which refer to the central zone between the pipes and the external part between the pipes and the borehole wall respectively.

In a similar manner, Bauer et al. (2011) developed a two-dimensional thermal resistance and capacity model (TRCM) for various

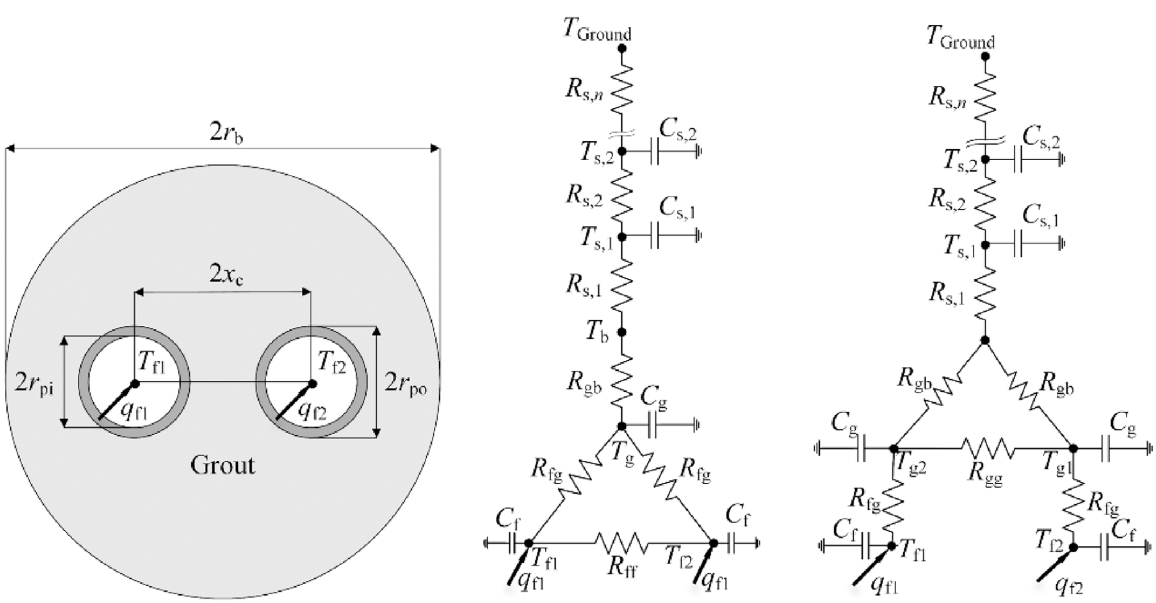

Fig. 1. Schematic figure of the equivalent thermal networks: (a) BHE, (b) STRCM of the present study and (c) The traditional TRCM (Bauer et al., 2011).