Geothermics 66 (2017) 110–118

Contents lists available at ScienceDirect

Geothermics

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

Borehole thermal energy storage systems under the influence of groundwater flow and time-varying surface temperature

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ARTICLE INFO

Article history:
Received 15 December 2015
Received in revised form 5 October 2016
Accepted 4 November 2016

Keywords:
Borehole thermal energy storage system
Ground heat exchanger
Spectral approach
Groundwater flow

ABSTRACT

A 3D finite element model of circular borehole cluster connected in series is used as a response model to generate normalized transfer functions of a borehole thermal energy storage system under the influence of ground surface temperature variations and groundwater flow. Two response functions are obtained by convolving transfer functions of the system's outlet fluid temperature with two incremental input functions describing the temperature variation of the inlet and outlet fluid and variations of the ground surface temperature. Superposition is applied to obtain the resulting fluid temperature with respect to thermal inputs at the inlet fluid and the ground surface over the course of ten years and results are compared for various groundwater velocities. This work demonstrates that the combined effect of groundwater flow and ambient air temperature variations can significantly decrease the performance of a BTES system. The methodology used can be extended to simulate complex system.

1. Introduction

In cold climates, borehole thermal energy storage (BTES) systems have the potential to significantly reduce the overall energy consumption since they allow seasonal storage of solar thermal energy. Numerous solar assisted heating ground source heat pump (GSHP) systems established in northern Europe and Canada are already operating successfully as they are providing district heating (Sibbitt et al., 2012; Lanini et al., 2014; Zhu et al., 2014).

BTES systems use ground heat exchangers (GHEs) such as closed loop vertical boreholes to exchange heat with the surrounding ground. During the summer, solar thermal energy is collected by solar collectors and stored in the geological medium through the GHEs. Depending on the temperature level, the thermal energy is extracted either by heat pumps (low temperature ground storage, 0–40 °C) or directly (high temperature ground storage, 40–80 °C) and delivered to the buildings during the heating season. Since the ground thermal conductivity is relatively low, heat losses by diffusion are considered moderate and storage efficiency can reach up to 70% (Reuss et al., 1997). However in presence of regional groundwater flow, heat advection can play an important role in the transport of thermal energy.

In recent years, some researchers studied the effect of groundwater on the heat transfer efficiency of GHEs by means of numerical models to account for various ground properties, heat load profile, borehole geometry, etc. For instance, Fan et al. (2007) developed a dynamic numerical model for vertical GHE with groundwater flow and showed that the impact of groundwater advection depends on groundwater velocities. Wang et al. (2009) found through experimental results that the performance of a single BHE was enhanced on average by 9.8% and 12.9%, respectively, compared with the case without groundwater flow. Choi et al. (2013) evaluated the combined effect of groundwater flow and geometrical arrays of a borehole field and its performance. Their results suggested that both direction and rate of groundwater flow may be important in designing the optimal GHE arrays.

Numerical methods are reliable but often cumbersome. For this reason, some authors used analytical approaches to model GHEs under regional groundwater flow. Capozza et al. (2013) superposed the so-called moving infinite line source solution (Carslaw and Jaeger, 1959) to model a borehole field under groundwater flow. Wagner et al. (2013) evaluated the applicability of the moving line source model to evaluate the thermal response of a grouted GHE. Chiasson and O'Connell (2011) compared the moving line source solution, the groundwater *g-functions* (Claesson and Hellström, 2000) and the mass–heat transport solution derived by using the mass transport analogy. Also, Tye-Gingras and Gosselin (2014) combined two analytical models: the infinite cylinder source (Carslaw and Jaeger, 1959) and the moving finite line source

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http://dx.doi.org/10.1016/j.geothermics.2016.11.002
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Nomenclature

C	specific heat capacity (J/(kg K))
f	impulse function (C)
g	transfer function
h	response function (C)
g_g	geothermal heat flux (W/m^2)
k	thermal conductivity (W/(m K))
H	borehole length (m)
P	period (h)
t	time (h)
t_d	time lag (h)
T	temperature (°C)
T_a	amplitude of the seasonal temperature variation (°C)
T_m	yearly mean ground surface temperature (°C)
z	depth (m)
$\dot{V}$	pumping flow rate per borehole (m^3/s)

Greek symbols

α	thermal diffusivity (m^2/s)
ρ	density (kg/m^3)
ν	velocity (m/s)
ω	angular frequency (1/s)

Subscripts

f	fluid
a	aquifer
b	borehole
g	grout
s	surface
D	Darcy
i	time step index
0	initial conditions

Acronyms

BTES	borehole thermal energy storage
BHE	borehole heat exchanger
GSHP	ground source heat pump

(Molina-Giraldo et al., 2011) and used spatial superposition to model a borehole field.

It is obvious that groundwater flow even at relatively low specific flow rates can significantly enhance heat transfer in the ground. For borehole thermal energy storage purpose; however, groundwater flow can be a nuisance in cases of compact configurations. Indeed, regional groundwater flow can drag the stored energy away from the borehole field. Few works in the literature focused on this topic. The modeling of a dynamic BTES system under regional groundwater flow can be quite complex as it must take into account thermal conduction and advection, which depends on local geological and hydrogeological parameters. The common approaches are based on the development of numerical models. For example, Bauer et al. (2009) found through finite element modeling that BTES systems are sensitive to regional groundwater flow. When compared to a case with no groundwater flow, a decrease of performance was observed after the fifth operating year. Yang et al. (2013) found similar results through numerical investigation with an implicit finite volume model.

In addition to heat advection driven by groundwater flow, heat exchange at the ground surface of the borehole field can be an important factor. In fact, Zarrella and Pasquier (2015) found through simulations of a GSHP system that ignoring the contribution of ambient air temperature variations does not always ensure a conservative design. This is particularly true if temperature differences between the ambient air and the borehole field are significant. Lanini et al. (2014) raised the importance to lay insulating materials over the BTES to reduce heat losses to the atmosphere, especially when seasonal variations of the ambient temperature are significant.

No studies were conducted to evaluate the combined effect of regional groundwater flow and ambient air temperature variations on the efficiency of a small BTES system. This present work focuses on the dynamic simulation of a small BTES system under the influence of regional groundwater flow and ambient air temperature variations. The analyses were based on a finite element model and comparison studies were conducted through a spectral approach.

2. Methodology

In the following section, the methodology used to simulate a complex dynamic BTES system is presented. First, Section 2.1 describes the finite element model of a BTES system used to generate transfer functions. Then, Section 2.2 presents the spectral approach proposed to generate the outlet fluid temperature of the system. Finally, Section 2.3 describes a ten year simulation scenario involving groundwater temperature variations, ground surface air temperature variations, groundwater flow and time-varying inlet fluid temperature.

2.1. Finite element modeling of a BTES system

A small BTES system composed of 18 short vertical closed loop GHEs is modeled by means of a finite element model similar to the model presented by Marcotte and Pasquier (2014) (the reader is referred to the initial paper for points of detail). The BTES system is represented in 3D with a symmetry plane and includes 742 750 degrees of freedom (Figs. 1 and 2). The system consists of six branches separated by an angular distance of 60 ° with three boreholes each connected in series and separated by a distance of 1.5 m. The boreholes are buried 2 m below the ground surface and have a length of 15 m each. The soil below the boreholes is also accounted for.

To operate the system, a heat carrier fluid flows from boreholes on the outer periphery towards the center boreholes. Although a typical load–unload operation consists to load from the center and discharge from the periphery of the BTES, the superposition principle which is utilized in this work requires the linearity of the problem and, currently, cannot account for a change of the flow direction. Additional development is still required to improve the simulation approach used in this work. The physical properties and dimensions used for the model are summarized in Table 1.

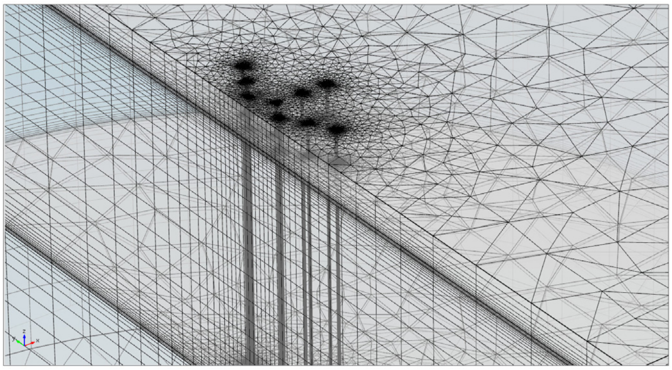

Fig. 1. Finite element model of the BTES system used in this work (see details in Table 1). Note that the boreholes are buried 2 m below the ground surface.