Energy Conversion and Management 77 (2014) 700–708

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Energy performance and thermal impact of a Borehole Heat Exchanger in a sandy aquifer: Influence of the groundwater velocity

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ARTICLE INFO

Article history:
Received 15 July 2013
Accepted 14 October 2013

Keywords:
Ground-Source Heat Pump
Borehole Heat Exchanger
Groundwater flow
Energy performance
Thermal impact
Numerical methods

ABSTRACT

In a saturated soil, the groundwater flow affects both the energy performance and the thermal impact on the surrounding soil of Borehole Heat Exchangers linked to Ground-Source Heat Pumps. In this paper a numerical model in MODFLOW/MT3DMS of a single U-pipe in a sandy aquifer is proposed in order to investigate the two issues in a coupled approach. After validating the model, the typical yearly operation of a Borehole Heat Exchanger extracting and injecting heat into the ground is simulated. For $0.1 \leqslant Pe \leqslant 1$ cold and warm plumes develop and the heat rate increases non linearly from 11% to 105%.

1. Introduction

Geothermal resources have a rising importance worldwide. Among direct utilizations of geothermal energy, Ground-Source Heat Pumps (GSHPs) are rapidly growing, so that in 2010 they accounted for the 68% of the installed capacity and for the 47% of the total energy use [1]. GSHPs are used to provide heating and cooling to buildings with a high energy efficiency or Coefficient Of Performance. The most common GSHPs are coupled with closed loop vertical boreholes, typically 100–150 m deep in the ground, with polyethylene U-pipes acting as Borehole Heat Exchangers (BHEs).

The energy performance of GSHPs strongly depends on the heat transfer process between the BHEs and the ground. In many applications the ground can be considered as a purely conductive medium, so that heat exchange depends on the thermal conductivity and the thermal capacity of the different ground layers. This hypothesis is generally at the basis of the commercially available tools used to design BHEs, such as GHLEPRO [2], EED [3], DST for TRNSYS [4] and RETScreen [5]. In turn on the academic side some efforts have recently been carried out to include the effects of the presence of a groundwater flow into the BHEs modeling [6–13]. In the presence of a groundwater flow the heat is transported also by convection, i.e. advection in hydrogeology [14]. Therefore two issues arise: on one side the correct prediction of the energy performance of the BHEs and their consequent design; on the other side the investigation of the thermal impact, or the temperature perturbation produced by the BHEs operation in the surrounding aquifer. The latter is also motivated by environmental concerns. Some countries actually adopted recommendations or legally binding thresholds for the distance among the BHEs and with respect to the property line [15]. The objectives are to limit the temperature anomalies in the aquifers and to minimize the mutual influence of neighboring GSHPs. Usually, to assess the temperature distribution in the aquifer, a simplified approach is adopted, by assuming that a given constant heat rate is either injected to or extracted from the ground. In this case, the BHE description in terms of U-pipe geometry and thermal-carrier fluid flow inside the pipe may also be avoided, and the BHE may be modeled as a line or cylindrical source, as in [7,16,10–13]. Clearly, in this simplified approach the coupling between the heat rate and the temperature field in the ground is disregarded. In reality the BHEs heat rate depends on the temperature conditions that develop in the surrounding ground.

Diao et al. [7] provide an analytical solution for the two-dimensional problem of an infinite line source in a saturated porous medium with a given Darcy flow (Moving Line Source or MLS), discussing the ground temperature response over time.

Molina-Giraldo et al. [16] extend the previous analytical approach to the case of a finite source (Moving Finite Line Source) and evaluate the axial effects on the ground temperature response. Their solution is expressed in dimensionless form by introducing the Péclet number as $Pe = U{\cdot}Z/a$, where U is the effective

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http://dx.doi.org/10.1016/j.enconman.2013.10.018

Nomenclature

C	volumetric heat capacity (J m^{-3} K^{-1})
c	specific heat capacity (J kg^{-1} K^{-1})
BHE	Borehole Heat Exchanger
GSHP	Ground-Source Heat Pump
H	hydraulic head (m)
h	convective coefficient (W m^{-2} K^{-1})
k	hydraulic conductivity (m s^{-1})
L	side (m)
LS	Line Source
$\dot{m}$	mass flow rate (kg s^{-1})
MLS	Moving Line Source
$\dot{Q}$	heat rate (W)
q	heat rate per unit length or specific heat rate (W m^{-1})
T	temperature (°C)
r	radius (m)
s	thickness (m)
t	time (s)
U	effective velocity (m s^{-1})
v	groundwater velocity (m s^{-1})

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
δ	dispersivity (m)
λ	thermal conductivity (W m^{-1} K^{-1})

Subscripts

g	ground
i	inlet
m	medium
o	outlet
s	solid
p	pipe
w	water
0	initial

groundwater velocity, the borehole length Z is adopted as the characteristic length and α is the medium thermal diffusivity.

In [10] the numerical finite-difference tool MT3DMS, widely adopted to simulate solute transport in porous media, is used to model a BHE in constant heat extraction mode. By comparing the model results with both an analytical solution (MLS) and other numerical solutions (FEFLOW, SEAWAT), Hecht-Mendez et al. [10] conclude that MT3DMS is suitable for modeling BHEs thermal impact in the aquifers.

Zanchini et al. [11] assess the effects of groundwater flow on the long-term performance of large BHEs fields with unbalanced winter and summer loads, in a dimensionless form, by finite-element simulations through COMSOL. They demonstrate that even low groundwater velocities provide an important improvement of long-term performance of the BHEs, by reducing the maximum annual value of the dimensionless temperature at the interface between the BHEs and the ground.

Hecht-Mendez et al. [12] numerically simulate the temperature response due to an arrangement of 25 BHEs and apply an optimization procedure adjusting the load pattern in order to minimize the thermal impact in the ground.

A numerical finite-element two-dimensional model in COMSOL is also created by Piller and Liuzzo Scorpo [13] and used to simulate the temperature distribution around a BHE. The results are compared to the MLS solution, showing a notable difference for relatively large Péclet numbers and in the close proximity of the boreholes.

In [6] a numerical finite-element approach is adopted, where the real U-pipe geometry is now described. The U-pipe is however run in constant heat flux mode, in order to simulate a Thermal Response Test under variable groundwater velocities. The effective ground thermal conductivities derived from the simulated test are then input in a commercially available GSHPs design tool to get the BHEs required lengths. The numerical groundwater flow and heat transport model is further used to simulate the long-term behavior of the BHEs fields, designed with the conventional methods and the thermal conductivities from the simulated Thermal Response Tests, finding that they are generally over designed.

Yet, if the purpose of the study is also to assess the heat exchange capacity and thus the energy performance of the BHEs, the heat source assumption has to be abandoned. This way, the energy and the thermal impact aspects are allowed to interact, so that a more correct evaluation of the temperature distribution in the ground can also be obtained. This second approach results in a higher computational effort and may be found in fewer studies, such as in [8,9].

Fujii et al. [8] develop a numerical model of a single U-pipe. The model is compared to the cylindrical source solution under the assumption of no groundwater flow, and then calibrated with Thermal Response Test data using the thermal conductivity of the medium as the matching parameter. A good agreement is found, although the experimental data used for the calibration refer to a very low groundwater velocity corresponding to a Pe $\sim 10^{-4}$, calculated taking the U-pipe diameter as the characteristic length, and thus the model is tested in heat transfer conditions dominated by conduction. The model is then used to evaluate the heat exchange rate after 5 days at increasing groundwater velocity. The increase due to groundwater flow appears negligible for Pe < 0.1 while it reaches about 100% for Pe $\sim$ 1. Further, a numerical model for the simulation of a large-scale BHEs field installed in the Akita Plain, Northern Japan, is created to evaluate the long-time operation. It is found that a minimum heat storage period of 2 months per year is necessary to avoid the decrease of the heat extraction rate with time.

Fan et al. [9] develop a finite volume numerical model of a large BHEs field in a saturated clay soil. The U-pipes are turned into equivalent single straight pipes and the BHEs model is coupled to a tool for the simulation of GSHPs. It has to be mentioned that in the paper validation data concerning the model are not available. The analysis shows that groundwater flow increases the performance of the GSHP if the BHE is used only to absorb heat, while it leads to a worse performance if a daily charge/discharge operation strategy is adopted.

Experimental studies on the BHEs operation in the presence of a groundwater flow are generally lacking. Only Wang et al. [17] conduct a thermal performance experiment of a BHE under groundwater flow in Baoding, China. They demonstrate that the presence of groundwater flow has an obvious influence on the temperature profile in the aquifer and, due to advection, the thermal performance of the BHE is enhanced by 10% and 13% in heat injection and extraction respectively. However, since the experiment is performed in real conditions and the groundwater flow cannot obviously be tuned, the BHE performance under null groundwater flow is not measured but simulated through TRNSYS.