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A moving finite line source model to simulate borehole heat exchangers with groundwater advection

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ABSTRACT

Available analytical models for the thermal analysis of ground source heat pumps (GSHPs) either neglect groundwater flow or axial effects. In the present study a new analytical approach which considers both effects is developed. Comparison with existing analytical solutions based on the finite and infinite line source theory is carried out. This study shows that in general the heat transfer at the borehole heat exchanger (BHE) is affected by groundwater flow and axial effects. The latter is even more important for long simulation times and short borehole lengths. At the borehole wall the influence of the axial effect is restricted to Peclet numbers lower than 10, assuming the BHE length as characteristic length. Moreover, the influence of groundwater flow is negligible for Peclet numbers lower than 1.2. As a result for Peclet numbers between 1.2 and 10 the combined effect of groundwater flow and axial effects has to be accounted for when evaluating the temperature response of a BHE at the borehole wall and thus the use of the moving finite line source model is required.

1. Introduction

Ground source heat pump (GSHP) systems are one of the major technologies for shallow geothermal energy production in many countries [1,2]. Through their use, significant amounts of fossil fuels can be saved and thus additional CO_2 emissions can be avoided [3,4]. GSHP systems are closed systems, in which a heat carrier fluid is circulated within a buried vertical or horizontal borehole heat exchanger (BHE). By slow and permanent circulation, exchange of heat with the surrounding underground is accomplished, which is utilized for space heating, air conditioning and hot water supply of both commercial and residential buildings. Vertical borehole configurations are often favored to horizontal collectors because of their smaller space requirements and because they are less influenced by seasonal temperature fluctuations from the surface. In this system, one or more vertical pipes are installed down to depths of around 50–150 m [5], depending on the prevailing geological conditions and the specific energy demand.

In order to estimate the heat transfer at the vertical BHE, different numerical [6–11] and analytical methods [12–21] as well as combination of the latter have been proposed [15,22,23]. Analytical solutions are widely used because of their simplicity and speed in computation. Most of the analytical approaches for the thermal analysis of BHEs presume conduction-dominated systems (i.e. natural groundwater flow is not considered), and they are based on the infinite line source or cylindrical source theory [13,15]. They are in particular applied for the evaluation of short-term geothermal field experiments such as thermal response tests (TRT) which usually range from 12 to 60 h [24]. These models, however, are less adequate for long-term simulations when axial effects become relevant, usually after 1.6 year of operation depending on the hydrogeological and operational conditions [25]. The temperature response for an infinite line source model (without groundwater flow) cannot reach steady state conditions and the temperature anomaly will increase to infinity with operation time.

In contrast, the temperature response converges to steady state conditions when accounting for a finite length of the borehole and hence axial effects are considered. Axial effects can be quantified as the differences between the results obtained by using finite and infinite line source methods. The axial heat conduction at the bottom of the borehole accelerates the heat exchange between heat carrier fluid and the surrounding underground, and thus has to be regarded for optimal borehole design. For a specific energy demand

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Nomenclature

a	thermal diffusivity (m^2/s)
c	specific heat capacity (J/kg/K)
Fo	Fourier number
H	borehole length (m)
K_0	modified Bessel function of second kind and order zero
n	total porosity
Pe	Peclet number
Q	heat flow rate extraction or injection (J/s)
Q_1	energy extraction or injection (J)
q_L	heat flow rate per unit length of the borehole (W/m)
r	distance to the source (m)
r'	radial coordinate (m)
R, R', Z, Z'	dimensionless coordinates
t	time (s)
T	average temperature of the porous medium (°C)
T_o	undisturbed initial temperature of the porous medium (°C)
ΔT	temperature change (°C)
v_T	effective heat transport velocity (m/s)
u_x	Darcy velocity (m/s)
x, y, z	space coordinates (m)

Greek symbols

λ	bulk thermal conductivity of porous medium (W/m/K)
ρ	density (kg/m^3)
φ	polar angle
ϕ,τ,ψ	integration parameters
Θ	dimensionless temperature

Subscripts

m	mean temperature around a circle
s	aquifer material (solids), steady-state
w	water

of a GSHP system, accounting for the axial effects can reduce the required length and numbers of boreholes. Marcotte et al. [26] showed for an example design problem that the calculated borehole length could be 15% shorter when axial effects are considered, which ultimately means a more cost-efficient system. Since under many circumstances the axial effects are of high relevance, apposite analytical solutions have been developed. Eskilson [15] proposed the finite line source model by summing up the effect of point sources of equal energy injection/extraction. This model was improved and used for the evaluation of long-term behavior of BHEs [18,27,28]. These analytical solutions account for the axial effects; however, they do not consider groundwater flow.

If groundwater flow is present, advective transport has to be considered, which means that heat is also transported by the moving water. Chiasson et al. [6], Wang et al. [29], Fan et al. [11] and Raymond et al. [30] evaluated the effects of groundwater flow on the heat transfer into the BHE. They concluded that groundwater flow enhances heat transfer between the BHE and the aquifer. In this case, shorter or less BHEs are needed for the same technical performance. Sutton et al. [17] and Diao et al. [14] presented an analytical solution considering groundwater advection. They both concluded that groundwater flow can change considerably the temperature distribution in the vicinity of the borehole. In these analytical solutions the borehole is considered as an infinite line heat source and therefore the axial effects are not taken into account in either study.

Hence, the aim of the present study is to develop an analytical solution which takes into account both aspects: groundwater flow and axial effects. It overcomes the limitations of previous analytical models especially for long-term simulation. The new analytical approach is verified with the finite element code FEFLOW version 6.0 [31]. This commercial software package was already used in several studies for simulating applications of shallow geothermal energy [e.g., 32,33]. The new analytical formulation is also compared to existing analytical methods in order to discuss the influence of axial effects and groundwater flow on the temperature development at the borehole wall and around the BHE.

2. Existing analytical approaches

The presence of groundwater flow in the underground and the influence of the actual length of the borehole are rarely taken into account when simulating heat transfer of GSHP systems. Therefore, conduction dominated systems are usually assumed and the borehole is approximated as an infinite line source. Few studies, however, have incorporated the effect of groundwater flow (moving infinite line source model) [14,17] or the axial effect (standard finite line source model) [15,18] in thermal analysis of BHEs. In the following section, these analytical models are presented.

There are other processes that influence the temperature response of the BHE, and therefore should be accounted for in other analytical solutions. Bandos et al. [12], for instance, developed finite length analytical solutions including vertical temperature variations caused by geothermal gradient and temperature fluctuations at the surface. Man et al. [16] proposed a solid cylindrical source model which considers the radial dimension of the BHE. The latter is suitable for short boreholes or piles in which the diameter becomes important in comparison with the installation depth. These approaches, however, are not shown in the present study and the focus of the paper is oriented to the combined effect of groundwater flow and axial effects.

2.1. Standard finite line source model – (FLS)

Traditionally, heat transport in porous medium without groundwater flow is described by the heat conduction equation [13], which can be expressed as follows:

$$\rho c \frac{\partial T}{\partial t} - \nabla \cdot (\lambda \nabla T) = 0 \tag{1}$$

where T denotes the average temperature of the porous medium in which local thermal equilibrium is assumed [34], λ is the bulk thermal conductivity, and ρc is the volumetric heat capacity of the bulk porous medium. The latter can be computed as the weighted arithmetic mean of the solids of the aquifer ($\rho_s c_s$) and water ($\rho_w c_w$) [35]:

$$\rho c = n \rho_w c_w + (1 - n)\, \rho_s c_s \tag{2}$$

The solution of the partial differential equation of heat transport (eq. (1)) for a continuous point source in an infinite porous medium with a uniform initial temperature (T_o) is given by [13]:

$$\Delta T(x, y, z, t) = \frac{Q}{4\pi\lambda r} erfc \left[\frac{r}{\sqrt{4at}} \right] \tag{3}$$

where ΔT is the temperature change in the underground $|T_o - T|$, Q is the heat flow rate extracted/injected, a the thermal diffusivity