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Multilayer analytical model for vertical ground heat exchanger with groundwater flow

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ABSTRACT

The vertical ground heat exchangers (GHE) are the most common application of the ground source heat pump (GSHP) systems. Due to ground heterogeneity and length of the boreholes, the heat exchangers cross usually several geological layers. However, in most of the current analytical models for GHEs, the restrictive assumption of ground homogeneity is considered. In this paper, a finite line-source model is proposed for GHEs that takes into account not only thermal conduction but also advection and dispersion mechanisms, induced by ground water flow, in a multilayer porous medium. Firstly, the anisotropy is added to the moving finite line-source (MFLS) model, and an existing composite model approach is modified. The temperature comparison with the numerical model results demonstrates the suitability of the approach. The proposed model provides faster solution than typical 3D numerical methods Furthermore, the homogeneous and multilayer assumptions are analyzed in dimensionless form to check the convenience of both of the approaches. The results demonstrate that, in case of high groundwater velocity in one layer, the thermal interaction with the neighboring layers decreases due to strong groundwater flow suppressing the thermal flux interaction. In that case, the prediction of homogeneous assumption is slightly sufficient in the middle of the layer. Otherwise, the multilayer approach is more appropriate in transient conditions, particularly, at the interface of layers.

1. Introduction

As an alternative and renewable energy source, the shallow geothermal energy evolves as one of the most popular energy source due to its easy accessibility and availability around the world. The ground source heat pump (GSHP) systems are the most frequent applications for extracting the energy from the shallow subsurface. As the heat extraction capacity of the GSHP system applications arises, the energy deficiency of the ground and the planning of the ground heat exchangers (GHE), which is the connected part of the system in the ground, become more important.

The market of the shallow geothermal energy (SGE) system technologies grows due to the promotion of its renewable energy source and regarding to the environmental structural policies of the governing institutions to mitigate the climate change (Bayer et al., 2012). Therefore, the long-term thermal energy efficiency of both of the system and the underground becomes of paramount importance to improve the operation performance of ground source heat pumps and to fulfill the required environmental policies.

In order to evaluate the necessary drilling depth and the regulation of the heat carrier fluid temperature, the specific heat extraction rate should be optimized regarding the characteristics of the hydro-geological conditions and the thermal properties of the ground for the long term operational effects (Bayer et al., 2014). For the planning and the design of GHE installations, the engineering guidelines (Stauffer et al., 2013; Kavanaugh and Rafferty, 2014; VDI-Richtlinie, 2001), thermal optimization methods (Hecht-Méndez et al., 2013; Sivasakthivel et al., 2014) and the software programs (de Paly et al., 2012; Blomberg et al., 2015) provide some tools to determine the length of the GHE and the optimization of the specific heat extraction rate depending on the heat demand.

For shallow geothermal system design and planning, the analytical heat source models demonstrate efficient performance compared to 3D numerical simulations that demand large computational efforts. However, the main limitation of available finite line-source and cylindrical source analytical solutions described in the literature is that

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Nomenclature

a	Thermal diffusivity (m2/s)
c	Specific heat capacity (J/kg/K)
H	Borehole length (m)
E	Bulk energy deficit in the ground
n	Porosity (-)
Q_P	Energy extraction or injection (J)
Q_L	Heat input per meter depth (J/m)
q_L	Heat input rate per unit length of borehole (W/m)
r_A	Radial distance of observation point a (m)
t	Time (s)
T	Temperature (K)
v_T	Thermal transport velocity (m s^{-1})
u_x	Darcy's velocity (m s^{-1})
x, y, z	Space coordinates (m)

Greek symbols

α_l	Longitudinal thermal dispersion coefficient
α_t	Transversal thermal dispersion coefficient
λ_m	Bulk thermal conductivity of porous medium (W/m/K)
λ_x	Effective thermal conductivity in the longitudinal direction (W/m/K)
$\lambda_y = \lambda_z$	Effective thermal conductivity in the transverse direction (W/m/K)
ρ	Density (kg/m3)

Subscripts

1	Layer 1
2	Layer 2
3	Layer 3
c	Composite
I	Imaginary
m	Medium
R	Real
s	Solid
w	Water

the thermal characteristics and the hydro-geological conditions of the ground are assumed uniform along the vertical depth of a GHE (Deerman and Kavanaugh, 1991; Eskilson, 1987; Zeng et al., 2002; Sutton et al., 2003; Diao et al., 2004; Marcotte et al., 2010; Man et al., 2010; Molina-Giraldo et al., 2011a; Erol et al., 2015). In reality the GHE may cross different layers along the depth with different hydro-geological and thermal properties for each layer. Therefore, the homogeneous assumption can lead unreliable results. In particular, to evaluate the long-term performance of the system, the consideration of the ground heterogeneity may allow the prediction of possible exhaustion of the heat reservoir in low conductive geological layers.

In order to evaluate the impact of multilayer ground conditions, several numerical investigations have been performed for short-term thermal response test (TRT) evaluations (e.g. a couple of days) (Signorelli et al., 2007; Lee, 2011; Florides et al., 2013; Raymond and Lamarche, 2013; Radioti et al., 2016). Lee (2011) developed a numerical (finite difference) multilayer model only for conduction, and according to their conclusion the traditional line-source models which assume homogeneous media are sufficient to estimate the ground thermal properties for the TRTs. Florides et al. (2013) presented a 3D numerical model (finite element method) which accounts only for conductive media to evaluate the fluid temperature along the length of a GHE. Signorelli et al. (2007) performed 3D numerical model to examine the influence of vertical heterogeneities along the length of a GHE during the operation of TRTs. They concluded that the heterogeneity may play an important role on the global behavior of GHE, particularly, if the groundwater flow is larger than 0.1 m per day.

Analytical method for multilayer heat transfer system requires additional complexities due to the combined boundary conditions and interactions between each layer. Several analytical models have been proposed to overpass the drawback for multilayer media (Ma and Chang, 2004; Abdelaziz et al., 2014; Sutton et al., 2002). Sutton et al. (2002) developed a multilayer algorithm by using the cylinder source model for only conduction mechanism and the algorithm requires additional data such as the downward and the upward temperatures of the heat carrier fluid, at each layer. Ma and Chang (2004) proposed an analytical solution for anisotropic multilayer media for heat conduction problems by using the linear coordinate transformation method. Abdelaziz et al. (2014) introduced a finite line-source model for vertical GHEs embedded in multilayer media. The method considers the calculation in two segments. (i) The first segment represents the layer in which the observation point is located. The finite line-source is taken into account in that layer with its depth coordinates. (ii) The second segment considers a single point-source located in each other layer and subjected to the geometric distances between the considered observation point and the point-source from both the real and the imaginary parts of the other layers. The thermal properties of different layers are taken into account in this segment as a composite model. The method provides fruitful results, however, considers only conduction.

An analytical solution that accounts for multilayer porous media with the groundwater flow and the anisotropy is of significant interest to evaluate the temperature change in the vicinity of the GHE, which is important for the planning in long-term operations. Furthermore, the prediction of the heat exchange rate in different layers may help also to optimize the design of the system by adapting the length of GHE as a function of the thermal characteristics of the geological layers. Our objective is to extend the capability of the existing composite method of Abdelaziz et al. (2014) by taking into account the groundwater flow and the anisotropy in different layers. We solve the Green's function which is the solution of the heat conduction/advection/dispersion equation in porous media and apply the method of images for a finite length of the line-source. Afterwards, the model is subdivided into segments with the multilayer approach to deduce the temperature evolution in the different layers along time. The developed model is validated by comparison with the results obtained from the finite element software COMSOL Multiphysics. Furthermore, we investigate the importance of this multilayer effect through a dimensionless comparison between homogeneous and multilayer configurations.

2. Analytical model for multilayer ground

2.1. Finite line-source model with groundwater flow and anisotropy

The general solution of the moving finite line-source (MFLS) model is already described by Molina-Giraldo et al. (2011a). Here in this section our contribution is to take into account the thermal anisotropy that may be induced by the groundwater flow.

The governing equation of the heat conduction/advection/dispersion in porous media is given as follows (Metzger, 2002):

$$\rho_m c_m \frac{\partial T}{\partial t} = \left(\lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2} + \lambda_z \frac{\partial^2 T}{\partial z^2} \right) - \mathrm{u}_{w,x} \rho_w c_w \frac{\partial T}{\partial x} + s \tag{1}$$

in which $\mathrm{u}_{w,x}$ is the Darcy's velocity assumed oriented in the x-direction, s is a volumetric heat source, and $\rho_m c_m$ is the volumetric heat capacity of the medium while $\rho_w c_w$ is the volumetric heat capacity of the water.