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3D numerical modeling of vertical geothermal heat exchangers

T.Y. Ozudogru [a,b,*], C.G. Olgun [b], A. Senol [a]

[a] *Department of Civil Engineering, Istanbul Technical University, 34469 Maslak, Istanbul, Turkey*
[b] *Charles E. Via, Jr. Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA 24061, USA*

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ABSTRACT

This paper presents the development and validation of a 3D numerical model for simulating vertical U-tube geothermal heat exchangers (GHEs). For minimizing the computational effort, the proposed numerical model uses 1D linear elements for simulating the flow and heat transfer inside the pipes. These linear elements are coupled with the 3D domain using the temperature field along the exterior surface of the pipe and an optimized finite element mesh for reducing the number of elements. The discretization of geometry, finite element mesh generation and the specifics of the system physics and boundary condition assignments are explained in detail. The model is used to simulate two generic cases, a borehole with a single U-tube and an energy pile with double U-tubes. In each case, a constant heating followed by a recovery period (i.e., no heating) is simulated. A review of the theory of finite line source model is also presented, along with modifications to account for variable heat rate. Moreover, a method to estimate the steady state thermal resistances in the borehole/energy pile is presented in order to calculate the fluid temperatures analytically. The validation of the model is carried out by comparing the numerical results with the results obtained from the analytical model.

1. Introduction and background

Geothermal heat pump (GHP) or ground-coupled heat pump (GCHP) systems are a promising and highly efficient renewable energy technology for space heating and cooling (Sanner et al., 2003; Lund et al., 2011). They are recognized by the Energy Star Joint Program as being among the most efficient and comfortable heating and cooling systems because they use the ground as a natural heat source and sink (Energy Star, 2013). Over the past 15 years, the technology has shown annual increases of 16.6% worldwide, with number of installed units at 2.76 million (Lund et al., 2011), which illustrates the high acceptance of this emerging technology in the heating, ventilation, and air conditioning (HVAC) market. By comparison with the conventional technologies, these heat pumps offer better levels of comfort, reduced noise levels, lower greenhouse gas emissions and reasonable environmental safety (Bandos et al., 2011). Electrical consumption and maintenance requirements of GCHP systems are lower than those required by conventional systems and consequently these systems have lower annual operating costs (Yu et al., 2002).

This technology relies on the fact that, after a depth of 5 to 10 m, the ground has a relatively constant temperature, warmer than the ambient temperature in the winter and cooler in the summer. A geothermal heat pump can transfer the heat stored in the ground into a building during the winter, and collect the heat from the building and inject it into the ground during the summer (Omer, 2008). Therefore, the efficiency of GCHP systems is inherently higher than that of air-source heat pumps because the average ground temperature serves a better baseline for heating and cooling in the winter and summer, respectively.

GCHP systems consist of a sealed loop of pipes, buried in the ground and connected to a heat pump (Bose, 1991). They use the ground as a heat source when operating in heating mode, with a fluid (usually water or a water–antifreeze mixture) as the medium that transfers the heat from the ground to the evaporator of the heat pump, thus utilizing near-surface geothermal energy. In cooling mode, they use the ground as a heat sink (Sanner et al., 2003). A vertical borehole configuration is usually preferred over horizontal trench systems because it requires less foot print and vertical systems bypass the shallow zone influenced by ambient temperatures and utilize the constant temperature of the ground. In vertical borehole systems, the geothermal heat exchanger (GHE) consists of a number of boreholes or energy piles, each containing several U-tubes. Energy piles are a relatively new ground-coupled heat exchanger technology in which the circulation pipes are

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[*] Corresponding author at: Department of Civil Engineering, Istanbul Technical University, 34469 Maslak, Istanbul, Turkey. Tel.: +90 212 285 6628.
E-mail addresses: ozudogru@itu.edu.tr, ozudogru@gmail.com (T.Y. Ozudogru).

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Nomenclature

A	cross-section area (m^2).
C_A, C_B	factors in Eq. (16)
c_p	specific heat capacity ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
d	diameter (m)
d_h	hydraulic diameter of pipe (m)
$\mathrm{Ei}(x)$	exponential integral
f_D	Darcy friction factor
h	overall heat transfer coefficient ($\mathrm{W\,m^{-2}\,K^{-1}}$)
H	length of the heat exchanger (m)
k	thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
Nu	Nusselt number
p	pressure (Pa)
q_{wall}	external heat exchange through pipe wall (W)
q	heat (W)
q'	heat flux per unit depth ($\mathrm{W\,m^{-1}}$)
q''	heat flux per unit area ($\mathrm{W\,m^{-2}}$)
r	radius (m)
R	thermal resistance ($\mathrm{m\,K\,W^{-1}}$)
Re	Reynolds number
T	temperature (K)
t	time (s)
t_s	time scale (s)
$\dot{V}$	volumetric flow rate ($\mathrm{m^3\,s^{-1}}$)
$\mathbf{u}$	velocity field ($\mathrm{m\,s^{-1}}$)
Z	wetted perimeter of pipe (m)

Greek symbols

α	thermal diffusivity ($\mathrm{m^2\,s^{-1}}$)
$\Delta T(t)$	applied temperature difference at time t (K)
ζ	distance between the actual point heat source and the point of interest (m)
ζ'	distance between the imaginary point heat source and the point of interest (m)
μ	dynamic viscosity (Pa s)
ρ	density ($\mathrm{kg\,m^{-3}}$)

Subscripts

b	borehole/pile
bw	borehole/pile wall
eff	effective
ext	external
f	fluid
g	ground
i	inside
in	inlet
int	internal
o	outside
out	outlet
p	pipe

integrated into a pile foundation that provides structural support for the building (Brandl, 2006). With vertical geothermal heat exchangers, geothermal heat pumps can offer both heating and cooling at virtually any location, with great flexibility to meet the energy demands (Sanner et al., 2003).

Over the years, various analytical and numerical models of varying complexities have been developed and used as a design tool for GHEs. Among other things, they can be used to predict temperatures in and around the GHE utilizing the heat transfer mechanisms inside a borehole, the conductive heat transfer from a borehole and the thermal interferences between boreholes. A number of design tools based on finite element or finite volume programs were used to develop fully discretized borehole heat exchanger models to include transient effects, as well as the correct borehole geometry. Some of the most noteworthy models include the studies by Al-Khoury et al. (2005), Al-Khoury and Brinkgreve (2006), Signorelli et al. (2007), Marcotte and Pasquier (2008), Lamarche et al. (2010) and He (2012). Some of the models were limited to 2D discretization because of the number of small elements needed for a sufficient discretization of the borehole cross section (Austin, 1998; Yavuzturk, 1999). On the other hand, several hybrid models were developed to provide a feasible alternative (Eskilson, 1987; Yavuzturk and Spitler, 1999). Such models are used to calculate the temperature response functions numerically. Analytical models, despite being less precise than numerical models, are preferred in most practical applications because of their superior computation time efficiencies and better flexibility for parametric design. The inaccuracy in the results of the analytical models corresponds to the underlying modeling assumptions made when deriving analytical solutions for GHEs. However, it must be kept in mind that uncertainties regarding the quality of input data may be more significant than uncertainties due to modeling approximations.

On the contrary, if a correct description of the geometry and heat transfer mechanisms inside and outside the GHE is needed, 3D numerical models must be used. Only 3D models can capture the vertical heat transfer inside and outside the GHE. They can be utilized to model layered ground profiles, the vertical gradient of the undisturbed ground temperature, the flow and transient heat transfer of the fluid inside the tubes, the thermal short-circuiting between the tube legs, and also they allow assigning proper boundary conditions at the upper and lower model boundaries. The main disadvantage of fully discretized 3D models is their extensive computation time, even with the help of modern and powerful computers and the possibility of parallel computing. For instance, a single simulation of an ordinary borehole thermal conductivity test takes from a few hours to several days. As a consequence, the application of fully discretized models for automated parameter estimation procedures with various iterations becomes impractical (Bauer et al., 2011).

In this study, we have developed a numerical modeling approach to overcome these problems. We utilized a commercially available finite elements simulation environment, COMSOL Multiphysics$^{\mathrm{TM}}$ (COMSOL, 2012) and developed a numerical model for vertical GHEs that can calculate the 3D transient heat and mass transport processes in the borehole and/or energy pile with satisfactory accuracy and minimal computational effort. This approach can be applied to automated parameter estimation procedures for thermal conductivity data evaluation. The proposed numerical model distinctively uses 1D linear elements for simulating the flow and heat transfer inside the pipes, which is fully coupled with the 3D geometry using the temperature field at the pipe exterior surface. In the recent studies by Corradi et al. (2008) and Zanchini et al. (2010a, 2010b), the distribution of the fluid bulk temperature along the flow direction and the heat transfer between the fluid and the pipe wall are evaluated by making use of weak form boundary condition available in COMSOL Multiphysics$^{\mathrm{TM}}$.

The model utilizes swept finite element meshing in the vertical direction, and the mesh is optimized to minimize the number of elements. However, the reduction should not be done at the expense of obtaining numerical results with poor accuracy. Prior experience shows that, mesh refinement is required near the ground surface, soil/rock layer interfaces and the toe of the heat exchanger, where larger vertical temperature gradients reside. Minimum refinement is necessary in mid-layers, where vertical temperature gradients are negligible. A similar meshing technique was used in a study by Marcotte and Pasquier (2008).