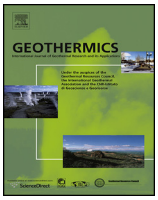
Geothermics 51 (2014) 406–416

Contents lists available at ScienceDirect

Geothermics

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



Multilayer finite line source model for vertical heat exchangers

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ARTICLE INFO

Article history:
Received 28 July 2013
Accepted 5 March 2014
Available online 29 March 2014

Keywords:
Geothermal
Energy pile
Heat exchanger
Line source
Layered ground

ABSTRACT

This paper introduces a finite line source model for vertical heat exchangers considering a layered soil profile. The existing analytical models assume a homogeneous soil profile, where the thermal properties of the ground along the entire length of the heat exchanger are uniform. This assumption can be unreliable since the typical length of heat exchangers is 60–100 m (200–300 ft.) and stratified ground is expected over this length. In the approach presented herein, the heat exchanger is divided into a number of segments to represent various soil layers along its length. Heat exchange induced temperature change at a certain location within the soil formation is evaluated by summing up the individual contributions of all these segments. The effect of the heat exchanger segment within the soil layer around itself is estimated using the finite line source model. Furthermore, the finite line source model is utilized on transformed sections for estimating the contributions of heat exchanger segments at locations outside their layer domains. The proposed model also incorporates two adjustments; the first accounts for the different heat rates within different soil layers while the second adjustment considers the heat exchange along the vertical direction between soil layers. Estimated results using the proposed model agree well with the results obtained from a calibrated finite element analysis. The proposed procedure is promising and can also be adapted within the framework of cylindrical models.

1. Introduction and background

Ground-coupled heat pump (GCHP) systems are utilized as an efficient sustainable energy technology for heating and cooling of buildings. This system consists of circulation tubes embedded horizontally or vertically in trenches or pre-drilled holes in the ground known as ground heat exchangers (GHE). The trench for horizontal systems is backfilled with the native soil while the pre-drilled holes for vertical systems are backfilled, in most cases, with thermally enhanced grout. The tubes are connected to a heat pump and a circulating pump at the ground surface which circulates water/antifreeze mixture in the tubes. GHEs are designed to inject or collect a certain amount of thermal energy via the circulating fluid (Sanner et al., 2003).

The design of any heating and air conditioning system and other system components is performed by first estimating the energy demand profile of the building. In addition to the typical distribution system design, the design of GCHP systems requires sizing of the heat pump and optimizing the heat exchanger length. The length of the heat exchanger depends mainly on the local regulations in the respective design region, the energy demand of the building, the type of the selected heat exchanger (vertical or horizontal), the thermal properties of the ground, and the undisturbed ground temperature. Therefore, the design of a GCHP system incorporates the building energy demands and heat exchange capacity of the ground. Estimating the building energy demand has been investigated by numerous researchers since the early eighties (McQuiston and Spitler, 1992; Pedersen et al., 1998) and has gone through significant improvements from simplified energy analysis (day hours, and bin method) to detailed building energy simulations (ASHRAE, 2009; Pedersen et al., 1998). Thus, the available techniques to estimate the building energy demand are considered adequate. On the other hand, the available analytical methods (line and cylindrical source models) related to modeling the heat

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http://dx.doi.org/10.1016/j.geothermics.2014.03.004
0375-6505/

Nomenclature

C_p	specific heat capacity (J kg^{-1} K^{-1})
erfc	error function
h	depth of the point of interest (m)
H	length of the heat exchanger (m)
k	thermal conductivity (W m^{-1} K^{-1})
L	length of heat exchanger segment (m)
LT	thickness of the transition zone (m)
M	mass (kg)
N	number of layers in the energy path
n	number of secondary segments of the heat exchanger = $N-1$
p_0	coordinates of the point of interest (x_0, y_0, z_0)
p_1, p_2	coordinates of the points at the beginning and at the end of the actual heat exchanger, $p_1 = (x_1, y_1, z_1)$ and $p_2 = (x_2, y_2, z_2)$
p_1', p_2'	coordinates of the points at the beginning and at the end of the imaginary heat exchanger, $p_1' = (x_1', y_1', z_1')$ and $p_2' = (x_2', y_2', z_2')$
Q	heat (W)
q	average heat flux per unit depth (W m^{-1})
q_i	layer-dependent heat flux per unit depth (W m^{-1})
r	radial distance between the heat source point and the point of interest (m)
R	effective thermal resistance (K m W^{-1})
S	distance that an energy way travels within a soil layer (m)
T	average temperature (K)
V	volume of a soil layer along an energy path (m^3)
X	depth of layer boundary (m)

Greek symbols

A	thermal diffusivity (m^2 s^{-1})
β	integration constant in Eq. (2)
τ	time (s)
ΔT	total temperature difference at the point of interest (K)
ΔT_{1-j}	temperature difference at the point of interest within layer j due to the primary segment of the heat exchanger (K)
ΔT_{2-ij}	temperature difference at the point of interest within layer j due to the secondary segment of the heat exchanger embedded in soil layer i (K)
ρ	distance between the actual point heat source and the point of interest (m)
ρ'	distance between the imaginary point heat source and the point of interest (m)
ξ	depth of the heat source point (m)
δ	integration variable refereeing to the location in the three-dimensional domain along the actual heat exchanger (m)
δ'	integration variable refereeing to the location in the three-dimensional domain along the imaginary heat exchanger (m)
γ	density (kg m^{-3})
∞	infinite
π	constant = 3.14159

Subscripts

i	soil layer number
comp.	composite section
upper	upper layer
lower	lower layer
interface	interface between soil layers

exchange within the ground are still constrained by several simplifying assumptions. One of these constraints is the homogeneous soil profile assumption (Carslaw and Jaeger, 1986; Ingersoll and Plass, 1948).

The design of GHEs involves two sets of analyses, one related to the domain inside the heat exchanger (tubes, infill material, fluid) and the other with the domain outside the heat exchanger (surrounding ground) as presented in Fig. 1. The former analysis is utilized to estimate the fluid temperature along the length of the heat exchanger considering the short circuit taking place due to the interaction between the two legs of the tubes (Zeng et al., 2003). The temperature at GHE/ground interface is used as a boundary condition for estimating the fluid temperature profile (Zeng et al., 2003). The interface temperature at any time is estimated from the latter analysis for the ground temperature outside the GHE. The fluid temperature is estimated by adding the heat loss taking place inside the GHE to the interface temperature assuming that the heat exchange inside the GHE has reached steady state condition which is represented by the borehole thermal resistance (Claesson and Eskilson, 1987). The borehole thermal resistance is evaluated by incorporating a series of thermal resistances including the convective resistance between the fluid and the inner tube surface, the conductive resistance of the tube walls, short circuit effect between down and up legs of the tubes, as well as the conductive resistance of the borehole backfill material (Man et al., 2010).

Based on Thomson (1884), different analytical models have been developed to simulate the heat conduction in the soil outside the GHE assuming no heat convection due to ground water flow. The infinite line source (ILS) model was developed by Ingersoll and Plass (1948) to estimate the temperature changes in an infinite homogeneous medium due to an infinite line GHE. A few years later, Ingersoll et al. (1954) proposed the infinite cylindrical source (ICS) model accounting for the cylindrical nature of the GHE. Then, the finite line source (FLS) model was proposed by Eskilson (1987) which considers the end effects of the heat exchanger. Lamarche and Beauchamp (2007) suggested improvements to the solution of the FLS method to decrease computational burden. Zeng et al. (2002) also used this model to study the long-term thermal behavior of vertical GHEs. Several efforts considering numerical models were reported in the literature including Lee and Lam (2007) who proposed a three-dimensional numerical model for GHEs, and compared their results to those obtained by the FLS and ICS models. Marcotte and Pasquier (2008) devised a computationally efficient method for the hourly temperature calculation with the FLS model. Furthermore, Marcotte and Pasquier (2009) used the FLS model to evaluate the influence of borehole inclination on the performance of a GHE system.

All of the above models are based on several simplifying assumptions including; (1) Homogeneous soil profile with temperature independent thermo-physical properties, (2) Uniform initial ground temperature, (3) Constant heat rate per unit length over the system operational period, and (4) No heat convection due to ground water flow.

Additional studies have been reported to overcome the limitations associated with these simplifications. For example, Bandos et al. (2009) developed an analytical FLS model accounting for the effects of the geothermal gradient and of the temperature changes at the soil surface. Carslaw and Jaeger (1986) and Sutton et al. (2003) proposed a moving line-source model to account for the