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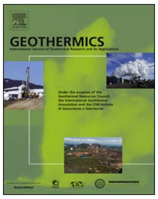

Numerical modelling of transient soil temperature distribution for horizontal ground heat exchanger of ground source heat pump

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ABSTRACT

A ground heat exchanger is the most important part of a ground source heat pump system. Soil properties and ground heat exchanger performance strongly depend on soil temperature profile and vary with time and space. Also, soil temperature profile is a function of heat transfer rate extracted or transferred to soil. Studies in the literature either use the unaffected soil temperature obtained from meteorological data or fail to run for long time periods to obtain a steady periodic soil temperature profile and over-predict the ground heat exchanger performance. Therefore, steady periodic temperature profile should be used for sizing ground heat exchanger for efficient operation of ground source heat pumps for longer periods of time. Experimental studies are carried out on a ground-source heat pump established at Yıldız Technical University, Davutpaşa Campus and the newly developed numerical model is validated with experimental results. For the numerical study, the hourly required heat load of a 200 m^2 office in Istanbul during the heating season is calculated by using HAP software. The transient soil temperature profile is obtained numerically for longer periods of time with realistic boundary conditions using meteorological data. The fluid inlet temperatures equivalent to the hourly need for heating load of the office during the heating season are simulated for a ten-year period in accordance with the different heat amounts extracted from unit pipe length in soil (21, 10.5 and 7 W/m). The effects of burial depth, distance between pipes and surface effects on soil temperature are also investigated. Horizontal and vertical temperature distribution in soil at the beginning (November 10th), middle (January 21st) and end (April 3rd) of the first, fifth and tenth years are represented.

1. Introduction

The increase in world population, people's aspiration to rise their life standards and rapid industrialization of countries have led to a substantial rise in energy consumption. In order to meet this energy demand, it is vital that existing energy sources should be used more economically and wisely, waste energy should be recycled and renewable energy sources should be preferred.

Recently Ground Source Heat Pump (GSHPs) have been extensively used for heating and cooling buildings. Being one of the renewable energy sources, they are among the most invested energy resources in the world, which struggles with energy and environment issues. Between 2010 and 2014, 49 countries invested approximately US$ 20 billion in geothermal energy for both direct-use and electric power (Lund and Boyd, 2015). The ground has higher temperatures than air during heating seasons and it is vice versa during cooling seasons. GSHPs have been developed in order to transfer ground energy to living areas. It is costlier compared to air and water systems.

As the Ground Heat Exchanger (GHE) is the most crucial component of GSHP systems, it is important that sizing of the GHE and burial depth should be determined by utilizing an effective method. The selection of these systems influences particularly the cost of entire GHE. Considering efficiency of the GSHP systems, the heat extracted from or dissipated to soil ought not to vary for longer period runs of GSHP systems. The composition and humidity of soil, pipe spacing and burial depth are also the key factors in order to design GHE (Demir et al., 2009).

There are two kinds of analytical approaches, namely the Kelvin Line Source Theory and the Cylindrical Source Theory. They both merely figure out symmetrical soil temperature distributions around the pipes (Chiasson, 1999). In the analytical model of Metz (1983), temperature distribution in the soil by separating the ground into blocks around the coil was obtained by modifying Line Source Theory. Mei (1991) included the effects of seasonal ground temperature variation, pipe material, properties of the liquid in circulation and he drew a comparison between the simple line source models and his modified

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Nomenclature

albedo	Reflectivity (−)
D_h	Sensible heat exchange coefficient (m/s)
e_a	Vapor pressure at air temperature (Pa)
f	Humidity and surface cover coefficient (−)
h_a	Heat transfer coefficient of air (W/m^2 K)
H	Simulation depth (m)
k_f	Fluid thermal conductivity (W/m K)
k_s	Soil thermal conductivity (W/m K)
L	Pipe length (m)
m_f	Mass flow rate of fluid (kg/s)
M	Module (number of parallel tubes)
P	Period (s)
$\dot{Q}_{max}$	Maximum heating load of extracted from soil (kW)
$\dot{Q}_{req}$	Required heating load of extracted from soil (kW)
$\dot{q}_e$	Heat flux due to moisture transfer (W/m^2)
$\dot{q}_h$	Heat flux due to convective heat transfer (W/m^2)
$\dot{q}_{er}$	Heat flux due to emitted long wave radiation (W/m^2)
$\dot{q}_{ir}$	Heat flux due to incident long wave radiation (W/m^2)
$\dot{q}_s$	Incident solar radiation heat flux (W/m^2)
$\dot{q}_t$	Total heat flux (W/m^2)
Ri	Richardson number (−)
S_a	Amplitude of solar radiation (W/m^2)
S_m	Average of annual solar radiation (W/m^2)
T_a	Air temperature (K)
$T_{f,i}$	Fluid inlet temperature (°C)
$T_{f,o}$	Fluid outlet temperature (°C)
T_i	Initial temperature (°C)
T_s	Soil temperature (°C)
$T_{s,a}$	Amplitude of soil temperature (°C)
$T_{s,m}$	Average soil surface temperature (°C)
T_y	Soil surface temperature (K)
U_z	Wind speed at a height of z (m/s)
V_f	Volumetric flow rate (m^3/h)
Y	Burial depth (m)
z_0	Roughness (m)
$C_{p,a}$	Specific heat of air (J/kg K)
$C_{p,f}$	Specific heat of fluid (J/kg K)

Greek letters

α	Soil absorptivity (−)
Δt	Time step (s)
α_s	Soil thermal diffusivity (m^2/h)
ε	Soil emissivity (−)
ζ	Stability function (−)
κ	Von Karman constant (−)
φ_1	Phase angle (rad)
ω	Angular velocity (rad)

line source model. While simplifying boundary conditions to solve equations analytically makes some error on results mainly in short-term simulations. Variation of soil temperature with depth and the surface effects do not take into account in analytical models. In some models, the effects of the convection at soil surface were contained (Bohm, 2000; Chung et al., 1999).

Piechowsky (1999) and Piechowski (1996) also examined Thermal Response Tests (TRTs) exploiting straight horizontal GHEs for various burial depths with a length of 12 m and suggested a numerical simulation model using the 2D finite difference method; thus, validated the model with TRT results. Demir (2006) and Demir et al., 2014) developed a code in MATLAB environment to examine the heat transfer of the horizontal parallel pipe GHE by using Alternating Direct Implicit method. In their experimental study, they inserted thermocouples buried in soil horizontally and vertically at different distances from the pipe center and at the inlet and the outlet of the GHE. By using experimental fluid inlet temperatures, the results of experimental and numerical simulation were compared. The experimental data and the numerical results were seen to be highly compatible in their work. Kayaci et al., (2015a,b) worked numerically on horizontal GHE especially about long-time soil simulation and effects of surface conditions on temperature distribution in the soil. Also, a new experimental setup

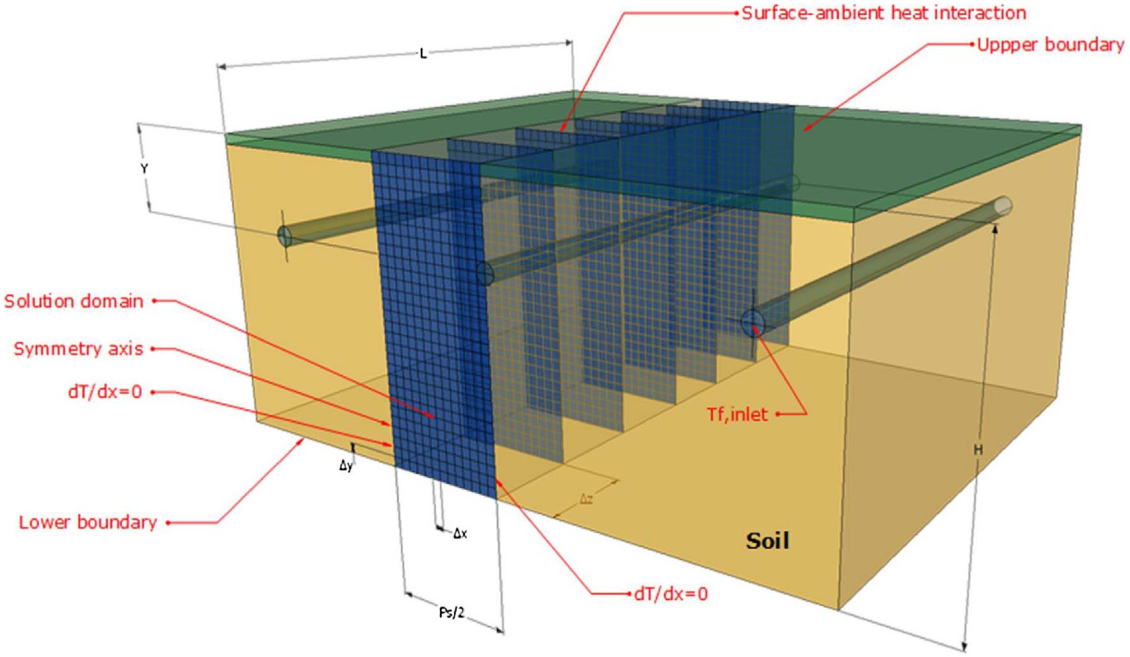

Fig. 1. Ground heat exchanger and solution domain.