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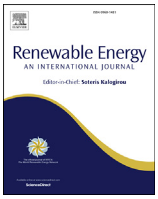

Thermal conductivity determination of ground by new modified two dimensional analytical models: Study cases

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ABSTRACT

Determining thermal conductivity of ground plays an important role in designing procedure of ground source heat pump (GSHP) systems. In this paper new modified 2D analytical models which are depending on thermal conductivity of ground are derived and results are compared with experimental ones. In an experimental study, a single borehole ground heat exchanger (GHE) with polyethylene U-tube pipe is considered for two different regions. Fluid is pumped into the pipes in a specific temperature and inlet and outlet temperatures are measured as well as volumetric flow rate. Analytical results curves are fitted to experimental one and thermal conductivities of ground are calculated for each region. Based on validated analytical models, long term performance of a single borehole GHE is determined. Additionally, temperature distributions around borehole GHE are investigated analytically in region 1 (N.D.B. residence region). Analytical models given in this study can easily help designers to evaluate thermal conductivity of ground and thermal performance of the borehole GHEs.

1. Introduction

Using of renewable energy sources becomes popular due to their large heating load and high efficiency [1]. Geothermal energy is known as one the most efficient renewable energies in the world. It is clean, sustainable, suitable energy storage and available for whole day. Geothermal energy can be used through ground source heat pump (GSHP) systems. Ground source heat pump (GSHP) systems are becoming widespread due to their high potential to considerably reduce the primary energy use of space heating and cooling compared with the conventional systems. They can be used for different purposes such as, supplying heating and cooling demands of the building, waste heat recovery of gas turbine exhaust gasses [2], snow melting on pavements and bridge decks, etc. [3]. For instance, as it is stated in Ref. [2], waste heat of micro gas turbine exhaust gasses energy can be stored in ground through ground heat exchangers (GHEs) and then recovered by GSHP system for supplying heating demands of the building. Balbay and Esen [3] developed new method for snow melting on pavements by using GSHP system. Their GSHP system consists of U-tube GHEs (vertical length: 30, 60 and 90 m) on pavements and bridge decks. The advantage of using GSHP system in their method is that, melting snow with a hydronic heating system can eliminate need for snow removal by chemical or mechanical means. In another study [4] GSHP system is integrated with solar system. The requirement for alternative low-cost energy sources has given rise to the development of new ground source heat pump systems for residential and commercial heating/cooling applications. Esen et al. [4] established slinky GHEs for a solar assisted GSHP. GSHP consists of two main part, heat pump and GHE. Each part highly influences GSHP system performance and are needed to be designed exactly [5–9]. GHEs are divided into shallow and deep ones. Shallow GHEs are helix, slinky etc. and deep one is generally U-tube pipes. U-tube GHEs are usually embedded in the borehole which is filled with grout [9,10]. When GSHP system start working, heat transfer process in ground around borehole is began. Therefore, analyzing this process becomes as an important problem for borehole designers [11,12]. There are different methods that can explore heat transfer procedure such as experimental study, analytical modeling and computational methods (Using software like FLUENT, ANSYS, COMSOL). Each method has its own advantages and disadvantages. Although experimental study gives almost exact results, its building's cost is high, not applicable everywhere and time consuming. Commercial software takes short period to reach results but their license's cost is too high and cannot be used by everyone. Between these methods, analytical models are almost favorable because of their clearness and reaching expected results in a short period.

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Nomenclature

c_p	Specific heat capacity of ground
T_i	Average temperature of inlet fluid
c_{pf}	Specific heat capacity of fluid
T_o	Average temperature of outlet fluid
D	borehole diameter
T_∞	Undisturbed ground temperature
h	Length of borehole
t	Time
H	Dimensionless length
$\dot{V}$	Volumetric flow rate
k	Thermal conductivity of ground
Z	Dimensionless z coordinate
k_P	Thermal conductivity of U-tube pipe
ρ	Density of ground
$\dot{m}$	Mass flow rate
α	Thermal diffusivity
$\dot{Q}_{\exp}$	Experimental HTR value
θ	Dimensionless temperature
$\dot{q}'$	HTR value per length of borehole
ϑ	Dimensionless time
r_b	Borehole's radius
r_e	Equal pipe's radius
r_{pi}	Inner radius of U-tube pipe
r_{po}	Outer radius of U-tube pipe
R	Dimensionless radius
T_{avg}	Average fluid temperature

Analyzing thermal properties of application area (ground) is one the most essential steps in designing procedure of GSHP systems. Therefore, thermal properties of ground such as thermal conductivity of it is needed to be determined. Thermal conductivity of ground can be simply calculated by fitting analytical (1D, 2D or 3D models) results to experimental ones. 1D analytical method is described in details in our previous work given in Ref. [13] and main goal of this study is to present 2D method. Another important part of GSHP designing procedure is to estimate thermal performance or heat transfer rate (HTR) of borehole accurately. HTR of the borehole will be decreased by the GSHP system operation time due to temperature rise or reduction around borehole. HTR is directly related to temperature differences between borehole wall and ground [11–14]. Therefore, it is necessary to find reliable model which can predict HTR of the borehole. Many research with different methods have done analysis on borehole modeling in literature [15–28].

Beier et al. [15] developed weighting factor for inlet and outlet temperature of vertical borehole GHEs. They derived 1D radial models than can give temperature variations with depth. They also validated their results by experimental ones and concluded that their models give more accurate results than the mean temperature approximation. Balbay and Esen [16] analyzed temperature distributions in pavement and bridge slabs which are heated by vertical GSHP systems. They developed 3D finite element models for modeling temperature distributions. They also validated their computational results by experimental ones. Their results show that thermal properties related to ground structure are very significant parameters in design of vertical GSHP system. Calvo et al. [17] introduced novel numerical method in ground source heat exchangers modeling. They decoupled short and long term analysis of borehole, borehole to ground model (B2G) was used for short term responses and g-function (In mathematics, the Barnes g-function is a function that is an extension of super factorials to the complex numbers) was used for long term ones. They believed that their novel model is faster and exact in both short and long term analysis. Conti et al. [18] gave analytical heat transfer models for a borehole which contains double U-tube. In their model, heat flux at borehole surface and return temperature with respect to various geometrical properties were evaluated. They used ε-NTU (effectiveness Number of Transfer Units) heat exchanger theory for models derivation. To investigate the effectiveness of their models, they compare results of double and single U-tube borehole ground heat exchangers. Hein et al. [19] constructed a comprehensive numerical model of borehole GHE which include flow and heat transport processes. The effects of various parameters on temperature evaluation around borehole was shown in their work. Holmberg et al. [20] studied on coaxial borehole heat exchangers numerically. They validated analytical results with temperature measurements obtained by thermal response test. Their model shows good accuracy in predicting the behavior of borehole heat exchanger. Furthermore, they investigate the effects of mass flow direction on borehole performance. Mingzhi et al. [21] presented a simplified heat transfer method which can examine efficiency of large scale borehole applications. They considered borehole geometric symmetry and assumed no water flow in ground in their modeling. Priarone et al. [22] developed a numerical model for temperature responses around borehole. Fourier equation was solved for different geometries and boundary conditions and the results were compared with available analytical results in literature. Selamat et al. [23] examined the optimization ways of horizontal GHEs by considering different layouts and pipe materials. They did 3D computational fluid dynamic (CFD) analysis during optimization process. Wang et al. [24] investigated the thermal behavior of horizontal geothermal heat exchangers with vertical spiral coils. Mathematical model was developed to analyze performance of these GHEs. Their model was validated by experimental and also simulation results. Furthermore, they showed temperature distribution around GHEs. Zhang et al. [25] gave optimum design of borehole heat exchangers. They simulated performance of the borehole hourly and determined optimum combination of distance between boreholes, borehole depth, diameter and annually heating/cooling load of the building. They used field test study to validate the effectiveness and feasibility of their model. Aydin et al. [26] investigate thermal performance of the borehole with different numbers of U-tube GHEs experimentally and analytically. They derived an analytical model which was fitted to experimental results. Furthermore, they made long term performance prediction of the borehole as well as cost analysis of it. Molina Giraldo et al. [27] developed a new mathematical method to investigate the thermal performance of the GHE by considering the effects of groundwater flow. They claim that fluid flow in ground highly affect the borehole performance. Gultekin et al. [28] determined HTR values of the borehole computationally by using COMSOL software. They also analyzed thermal interaction between boreholes in large area applications and determined optimum distance between borehole as well as temperature variations.

One of the most important parameters which highly affects thermal behavior of borehole GHE in GSHP applications is thermal conductivity of ground. The goal of this study is to find simple, feasible, accurate and reliable analytical model which can