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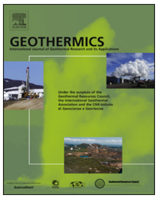

Review of effective thermal conductivity models of rock-soil for geothermal energy applications

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ABSTRACT

In recent years, the utilization of geothermal energy through ground buried heat exchanger to provide heat source for buildings has become extremely attractive within China and all over the world. The effective thermal conductivity of the ground, which may affect the heat transfer process between the buried pipes and the surrounding rock-soil significantly, is a key parameter that governs the prediction of the system performance. This article reviews recently proposed methods to determine the effective thermal conductivities of different rock-soil types containing various substances. The applicabilities of various basic methods to include the effects of porosity, water content, material construction and etc. are documented. According to the deficiencies of basic models, the improved models take into account the effects of the temperature, saturation degree, detailed structure of rock-soil and other parameters to improve the accuracy of predictions. For certain types of rock-soil, experimental measurements are needed to improve the accuracy or verify the results of the improved model in the appropriate ranges of porosity and saturation degree. However, these measurements tend to be expensive and time consuming.

Subscripts*a*Air phase*dry*Dry soil*l*Liquid phase*lower*Lower value*q*Quartz*o*Other minerals*r*Normalized*s*Solid phase*sat*Saturated soil*ug*Undisturbed*upper*Upper value△DifferentialSuperscript*Reference value

1. Introduction

The worldwide energy crisis calls for the need to use renewable energy, such as geothermal energy, which has taken greater importance than before. Different types of pipes are placed underground at the desired depth to absorb heat from the high temperature rock-soil. This heat flows from the high temperature rock-soil through the pipe wall of the exchanger to the working fluid inside the pipe. The working fluid circulates continuously between the buried pipe and the system above the ground section, carrying heat from the ground to the thermal equipment for further use.

There are many factors that may affect the performance of the above-mentioned system, including but are not limited to, the climate, the structure and the material of the buried pipe, the flow rate and properties of the working fluid, the thermal properties of the ground, and etc. The structure and the material of the buried pipe affect the costs of the system. The flow rate and properties of the working fluid determine the pumping power and the heat recovery rate. The flow rate can be adjusted according to the heating requirement. The climate may have impact on the shallow layer temperature of the ground. Among these factors, the effective thermal conductivity of the ground is an important factor in terms of heat transfer between the external wall of the buried pipe and the ground as well as the heat conduction in soil, which dominates the heat exchange potential of the whole system during operating process. It can be seen from Fourier's law of heat conduction that the heat transfer area, the temperature gradient, together with the thermal conductivity determine the amount of heat exchange in a conduction process. Once the position and the structure of the pipe (including inner and outer diameters, length, and thermal properties) are fixed, the first two terms become constant values and are not difficult to acquire. During the starts-up period, the temperature distribution of the rock-soil changes continuously. This would in turn affect the performance of the system. According to the line source theory, in the surroundings of the borehole, the temperature distribution can be expressed as (Morgensen, 1983),

$$T(r,\,t) = T_{ug} - \frac{Q}{4\pi\lambda} Ei\left(-\frac{r^2}{4\alpha t}\right) \tag{1}$$

where $T(r,t)$ is the temperature of the rock-soil at distance r from the

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Nomenclature

a	Thermal diffusivity of the ground ($\text{m}^2\cdot\text{s}^{-1}$)
F_0	Dimensionless time
f	Transfer function
H	Effective bore depth (m)
L	Cube half side
n	Porosity
Q	Injected heat power rate (W)
P	Dimensionless length
q	Heat flux ($\text{W}\cdot\text{m}^{-2}$)
R_b	Thermal resistance between the fluid and the borehole wall ($\text{K}\cdot\text{W}^{-1}$)
r	Distance from the borehole (m)
r_b	Borehole radius (m)
S_r	Degree of saturation [%]
T	Temperature (K)
t	Time (s)
w_{ij}	Weight of the connection joining the *j*th neuron
x_i	Input of the *i*th neuron in the previous layer
x_j	Volumetric proportion of the component *j*
y_j	Transformed output by the *j*th hidden neuron

Greek Symbols

α	Normalized thermal conductivity
γ	Euler's constant (≈ 0.5772)
ς	Quartz volume fraction
η_1,η_2	Coefficients as functions of the pore structure
θ_j	Bias at the *j*th neuron
κ	Emperical parameter
λ	Thermal conductivity ($\text{W}\cdot\text{m}^{-1}\,\text{K}^{-1}$)
λ_j	Thermal conductivity of the rock-forming mineral *j*
ρ	Density ($\text{kg}\cdot\text{m}^{-3}$)
ϕ	Volumetric fraction

borehole after t seconds running, T_0 is the undisturbed ground temperature, Q_z is the heat flow per unit length, *Ei* represents the exponential integral, λ is the thermal conductivity and α is the ground thermal diffusivity. It is evident that the temperature of the rock-soil at a given position and time is a function of the thermal conductivity of the rock-soil, which influences further the temperature difference between the borehole and the ground, therefore affects the prediction of the system performance. Thus, it is a crucial problem to accurately model the thermal conductivity of the ground. Besides, the thermal conductivity of the rock-soil is essential for the optimal design of the buried heat exchange system because it determines the heat exchange per unit length of the borehole, and consequently affects the minimum length of the buried pipe and the installation costs (Fujii et al., 2009). Kavanaugh (2000) stated that 10% variation in the test of thermal conductivity could lead to 4.5%–5.8% design error of the borehole depth. The more accurate information on the rock-soil properties are acquired, the more costs can be saved by allowing the length of the ground buried pipe to be reduced (Hwang et al., 2010).

Generally speaking, the thermal conductivity of porous rock-soil is affected by various physical properties including but are not limited to, the density, the porosity, the volumetric proportion of different components, the grain size, the saturation ratio and so on. The structures and properties of the rock-soil at different positions and different depth may be different. Even at the same depth, the nearby rocks may also show disparate thermal properties due to the change of geological structure. Extensive research has been conducted to estimate the ground properties through theoretical methods and experimental approaches based on reasonable simplifications. Rees et al. (2000) conducted a review of the ground heat transfer effects on the thermal performance of the ground buried heat exchangers. They described the mechanisms of ground heat transfer and presented an overview of the methods available to solve the heat transfer problem during the design process. They then explained the methods to estimate the thermal properties of the soils. They introduced the expression forms of theoretical models including the parallel model, the weighted arithmetic mean method, the weighted arithmetic mean equation, the weighted geometric mean method, the De Vries model (De Vries, 1963) and the Van Rooyen and Winterkorn's model (based on the original work of Nusselt (1916) on the thermal conductivity calculation) (Van Rooyen and Winterkorn, 1957). The Makowski and Mochlinski's method (Makowski and Mochlinski, 1956) as well as the Thomas' method (Thomas et al., 1994) were also mentioned as empirical equations. The authors briefly described the meaning of the different parameters in the equations and the applicability of the above methods before solving the ground heat transfer equations.

Wang and Pan (2008) made a review on the challenges and difficulties in the prediction of complex multiphase materials and theoretical models to calculate the thermal conductivity. The main difficulties in evaluating the properties of multiphase materials came from their inherent variations, randomness, as well as the coupling between the components of different phases. The authors divided the existing thermal conductivity models into two parts. The two-component models, including the series and parallel models, the network models (decomposing complex microstructure of multiphase material into a network consisting of a set of series and parallel elements) (Agari and Uno, 1986; Bouguerra, 1999; Lehmann et al., 2003; Liang and Ji, 2000; Staggs, 2002; Yu and Li, 2006; Liang and Qu, 1999) and theoretical bounds (upper and lower bounds of the thermal conductivity) (Hashin, 1983; Hashin and Shtrikman, 1963; Zimmerman, 1992; Schapery, 1968;) were analyzed. Multiphase cases (mainly for the unsaturated soils) included empirical equations (connect the fractions of multiphase components with experimental data) (Cosenza et al., 2003; Friedman, 2005; Miyamoto et al., 2003; Batchelor and O'brien, 1977; Alharthi and Lange, 1987), modified mixing models (directly extend the two-component model to multiphase cases or treat the multiple phases as one single phase) (Woodside and Messmer, 1961; Dobson et al., 1985) and analytical solutions from the physical laws (replace the actual structure with simplified model) (Friedman, 1998; Dagan, 1989; Tinga et al., 1973; Miyamoto et al., 2005; Gori and Corasaniti, 2003). The authors noted that the capability of the existing theoretical models to predict the effective properties was greatly limited because they were based on simplified physics with over-idealized assumptions. Efforts in combining models with complex structures or measurement data might lead to improving the accuracy of the models but would narrow the range of their applicability. Besides, the numerical methods and experimental results were also presented to compare with the theoretical prediction results.

Dong et al. (2015) did a review on the thermal conductivity models for unsaturated soils. They concluded that the thermal conductivities of the rock-soil were governed by the factors including the mineralogy, the particle size, the particle shape, the packing geometry, the stress level, the water content, the porosity, the gradation and the cementation, which could be further generalized into the following elements: thermal conductivity of different constituent, type of soil, water content and particle contact. They categorized the existing models into three groups based on their principles. Mixing models conceptualized the soil system as a combination of series and parallel blocks to represent different components (air, solid and water). Empirical models built the relationship between the thermal conductivity and water content by normalizing the effective thermal conductivity or using thermal