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Research of heat and moisture transfer influence on the characteristics of the ground heat pump exchangers in unsaturated soil

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ABSTRACT

In recent years, the ground source heat pump (GSHP) system has been widely used due to its high unit efficiency, considerable energy conservation and low operating cost. However, the heat transfer efficiency of ground heat exchangers (GHE) in some projects decreases year by year. This results in the decrease of performance of the GHSP system. This is mainly because of lacking of the deep research about the heat and moisture transfer influence on the GHE in unsaturated soil. In this paper, a new model for predicting the soil thermal conductivity under different temperatures was developed. By comparing with the Campbell and de V-1 models, the new model showed better performance on predicting the soil thermal conductivity. Thereafter, a coupled heat and moisture transfer model in unsaturated soil was established for the GHE. In addition, the mode1 was verified by comparing its results against those established by other researchers. By the results, it was found that the model calculation results agreed well with the experimental data in the literature. Finally, the effects of different factors, including the soil types, soil porosity on the characteristics of the GHE were studied.

1. Introduction

In recent years, the ground source heat pump (GSHP) system, using the shallow underground geothermal energy to provide space heating and cooling, has been widely used due to its high unit efficiency, considerable energy conservation and low operating cost [1,2]. Vertical U-tube ground heat exchanger (GHE) is a key component and plays a decisive role on the operation performance of the GSHP system. Thus, many researchers have carried out considerable investigations on the ground heat transfer processes, especially the heat transfer model.

The common heat transfer models such as the line source model [3–5] and cylindrical source model [6,7], which both are based on analytical method, are two kinds of representative constant heat flux models of the GHE. In addition, some numerical models [8–11] are used to study the performance of a GHE. As the development of the GHE model, the impact of groundwater flow on the heat transfer between GHE and its surrounding soil have attracted broad attention [12–15]. Zhang et al. [16] presented a new spiral source heat transfer model which took heat conduction and convection of groundwater into account. Fan et al. [17] reported a GHE mathematical model considering the effect of the coupled heat conduction and groundwater advection on the heat transfer between the GHE and its surrounding soil. Barcenilla et al. [18] analyzed the 'effective' thermal conductivity correlation to analyze vertical heat exchangers with groundwater flow.

However, most of these models are based on a heat conduction process between GHE and its surrounding soil, or the effect of ground flow on the heat transfer for the GHE are considered in saturated soil. In practice, the heat transfer process between GHE and its surrounding soil is a dynamic coupling process involving the heat transfer and moisture transfer, which impacts on the thermal properties of soil parameters, and which in turn affects the heat exchange performance. These models might cause calculation error in the prediction. Therefore, the GHE model couple with heat and moisture transfer has been studied by many scholars [19–21]. Piechowski [22] developed a mathematical model, coupled with heat and mass transfer, for studying the effect of the initial soil moisture content on the thermal performance of a GHE. A mathematical model which takes into account the effects of the temperature gradient on the moisture migration was developed by Luikov [23]. Philip and Vries [24] presented a moisture

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Nomenclature

f_w	An empirical weighting function
h	Enthalpy ($J\,kg^{-1}$)
g	Shape factors
k_i	Weight factor
n	Constant which related to the soil types
q	The rapidity of the transition from air-to water-dominated conductivity ($m\,s^{-1}$)
r	Radius (m)
x	Volume fractions (%)
H_r	The latent heat of vaporization of water ($kJ\,kg^{-1}$)
$\bar{J}$	Flux ($kg\,m^{-2}\,s^{-1}$)
T	Temperature (K)
R_v	Water vapor constant ($J\,kg^{-1}\,K^{-1}$)

Greek symbols

τ	Time (h)
c	Specific heat ($kg\,m^{-3}$)
ρ	Density ($kg\,m^{-3}$)
λ	Thermal conductivity ($W\,m^{-1}\,K^{-1}$)
ε	Porosity (%)
θ	Volume fraction ($m^3\,m^{-3}$)

Subscripts

a	Gas
m	Mineral
s	Solid
sim	Simulation
v	Vapor
w	Water
wo	Water content

migration model at inhomogeneous temperature profiles, in which moisture migration affected by temperature gradient was taken over. Taking the fluid axial convective heat transfer and thermal "short-circuiting" among U-tube legs into account, Zeng et al. [25] established a new quasi-three-dimensional model for vertical GHEs. Based on heat and moisture transfer, Li et al. [26] presented an inner heat source model which takes into account of moisture migration in soil, soil type and soil porosity.

As noticed in the aforesaid literatures review, the thermal properties of soil parameters were considered as a constant in these mathematical models, the study of the effect of the variation of soil thermal properties on the characteristics of the GHE has been reported rarely. In addition, it is difficult to find a universal mathematical model to solve the problem of coupled heat and moisture transfer in some porous materials because of it depends on the GHE geometry, local soil and climatic conditions. Therefore, it is important to develop a mathematical model that can accurately predict the heat and moisture transfer in unsaturated soil. In this paper, firstly, a new mathematical model for predicting the soil thermal conductivity under different temperatures is developed, which is based on the Campbell model [27] and de V-1 model [28]. Secondly, due to the most important heat and moisture transfer processes are taking place in the vicinity of the pipe, a coupled heat and moisture transfer model in unsaturated soil is established for a vertical U-tube GHE of GSHP as well as to enhance the accuracy of the model. In addition, the mode1 is verified by comparing its results against those established by other researchers. Finally, the effect of different factors, including the soil types and soil porosity on the characteristics of the GHE are studied.

2. The new thermal conductivity mathematical model developed

The models of Campbell and de V-1 were analyzed through the experiment by Liu et al. [29]. The results showed that the calculated values agreed well with the experimental data, but there was still some deviation with the actual situation. Firstly, the main reason of this kind of phenomenon was that four parameters (x_{wo}, q_o, g_a and λ_s) were obtained by fitting test data in the Campbell model, leading to the results with wide deviation in the experimental data. Second, the effect of temperature on the soil solid thermal conductivity was neglected. In addition, the shape factors of each component were supposed a constant value that it did not agree with the actual situation. For the de V-1 model, it was more complicated than the Campbell model due to the moisture content was divided multiple range and calculated respectively.

Based on the models of Campbell and de V-1, a new mathematical model for predicting the soil thermal conductivity is developed in this paper. Because of four parameters (x_{wo}, q_o, g_a and λ_s) were obtained by fitting test data in the Campbell model, and the results were not ideal compared with the test data. Therefore, in this paper, two parameters (g_a and λ_s) of them in Campbell model can be calculated by the method of de V-1 model. According to this method, the soil solid thermal conductivity (λ_s) and shape factors are considered soil solid components, and including the effect of temperature on the soil solid thermal conductivity (λ_s). The new model will be more accurate and have a wider range of application.

The new model use to predict thermal conductivity of soil is similar to that of Campbell model. It is based on the assumption that the thermal conductivity of soil is that the weighted average of the conductivities of components of the soil. The overall thermal conductivity of the soil can be given by

$$\lambda = \frac{k_m x_m \lambda_m + k_w x_w \lambda_w + k_a x_a \lambda_a}{k_m x_m + k_w x_w + k_a x_a} \tag{1}$$

where, x, volume fractions, [%]; m, mineral; w, water; a, gas; λ, thermal conductivity.

In order to reduce some of the subjectivity and complexity of the method, a "fluid" thermal conductivity is defined as

$$\lambda_f = \lambda_a + f_w(\lambda_w - \lambda_a) \tag{2}$$

where f_w is an empirical weighting function given by

$$f_w = \frac{1}{1 + (\frac{x_w}{x_{wo}})^{-q}} \tag{3}$$

where x_{wo} is the water content at which water starts to affect thermal conductivity, [$m^3\,m^{-3}$]; q is the rapidity of the transition from air – to water dominated conductivity, [$m\,s^{-1}$]. The q can be expressed as

$$q = q_o(\frac{T}{303})^2 \tag{4}$$

where T is the Kelvin temperature of the soil, [K].

According to Eq. (1), the weighting factors then become

$$k_a = \frac{1}{3}\left[\frac{2}{1 + \left(\frac{\lambda_a}{\lambda_f} - 1\right) g_i} + \frac{1}{1 + \left(\frac{\lambda_a}{\lambda_f} - 1\right)(1 - 2g_i)}\right] \tag{5}$$

$$k_w = \frac{1}{3}\left[\frac{2}{1 + \left(\frac{\lambda_w}{\lambda_f} - 1\right) g_i} + \frac{1}{1 + \left(\frac{\lambda_w}{\lambda_f} - 1\right)(1 - 2g_i)}\right] \tag{6}$$