Renewable Energy 76 (2015) 7–15

Contents lists available at ScienceDirect

Renewable Energy

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

Finite difference modeling of heat distribution in multilayer soils with time-spatial hydrothermal properties

Hossein Nowamooz [a,*], Saeid Nikoosokhan [a], Jian Lin [b], Cyrille Chazallon [a]

[a] ICUBE, UMR 7357, CNRS, INSA de Strasbourg, 24 boulevard de la Victoire, 67084 Strasbourg, France
[b] ICUBE, UMR 7357, CNRS, Université de Strasbourg, 72 route du Rhin, 67400 Illkirch, France

A R T I C L E I N F O

Article history:
Received 14 September 2014
Accepted 4 November 2014
Available online

Keywords:
Finite difference method
Multilayered soil heat distribution
Time-spatial variable thermal diffusivity
Homogeneous soil

A B S T R A C T

In this study, the heat distribution throughout the profile of unsaturated multilayered soil is determined using finite difference method while its thermal diffusivity varies with time and depth. First, the input parameters such as water content, dry density and sand content of the soil profile are provided. These data are coupled with the theoretical approaches to estimate thermal properties of soil such as thermal conductivity and thermal diffusivity of multilayered soil. Second, finite difference method is used to model heat distributions in soil profile taking into account the initial and boundary conditions. A continuity of heat flux between each layer is performed as a condition in the numerical model. A comparison of estimated temperature within time throughout the profile with the thermal probe measurements shows a satisfactory capacity of the numerical model. Finally, different cases of nonhomogeneous and homogeneous soil show that thermal response of homogeneous and nonhomogeneous soils are almost similar at average value of thermal diffusivity where hydrothermal characteristics of each soil layer (such as water content, dry density, and soil texture) are required to calculate this average value.

1. Introduction

A shallow geothermal energy system is considered as a significant source of thermal energy suitable for heating and cooling of individual buildings. It is a renewable source of energy as heat transfers continuously in the soil due to temperature gradient between the bottom of the earth and the air [1].

Since 1980, researchers have widely considered soils for heating or cooling purposes of seasonal thermal energy storage applications, e.g., Refs. [2–8]. Thermal energy can be stored for long time in the underground soil [9]. The development of ground coupled heat pump (GCHP) has been promoted since environmental problems exist [10–12]. Several advantages of using underground soil as heat source for GCHP compared with the traditional air source heat pump, encourage researchers to understand more about thermal behavior of soil [13–16].

Soil temperature is considered to be an important parameter in geothermal energy applications such as the passive heating and cooling of buildings including performance, dimensions, and installation cost in many geothermal applications [17–20]. In shallow grounds, just 20 m below the surface, the soil maintains nearly constant temperature ranging between 10 and 20, depending on the region [21]. In this context, for the seasonal heat storage (studied in this work) such as earth to air heat exchanger (EAHEs), and GSHPs, the soil temperature is considered to be nearly constant for the depths higher than 20 m [22–24].

Hydrothermal properties of soil have been widely studied in geothermal issues. Soil thermal properties are important inputs for models of soil temperature, but those thermal properties vary while the water content in soil changes. Many researchers have studied the dependence of thermal diffusivity of soil with other soil characteristics as well as degree of saturation [25–30]. However, conventional schemes consider constant thermal properties to give hydrothermal response of soil [31–33]. Ozgener et al. [34] developed a model to predict daily soil temperatures using a sinusoidal function of time and depth. In their work, transient heat flow principles were used with assumptions of one dimensional heat flow, homogeneous soil, and constant thermal diffusivity. Such hypothesis cannot take into account a comprehensive understanding of the effects of thermal properties due to the fact that those properties vary with soil physical characteristics such as soil texture and water content.

* Corresponding author.
E-mail address: hossein.nowamooz@insa-strasbourg.fr (H. Nowamooz).

http://dx.doi.org/10.1016/j.renene.2014.11.008
0960-1481/

Furthermore, the commercial computer codes taking in consideration the hydrothermal properties variation are not able to attribute different hydrothermal properties of different soil layers for a same profile. It is necessary to develop a code which can calculate the variation of hydrothermal properties of multilayers for one soil profile while applying heat flux continuity at the interface of each layer of soil profile.

In this study, the input parameters of an in-situ soil such as water content, dry density, and sand content of the soil profile are initially measured for different layers with time and depth. Using theoretical approaches, thermal properties of multilayered soil such as thermal conductivity and thermal diffusivity are also determined for the different time and depth. Finally, the finite difference model is applied on this multilayered profile to capture its temperature variation with time and depth.

2. Numerical model

In this section, heat distributions throughout a multilayer profile of soil are obtained by considering variable thermal diffusivity. Fig. 1 shows a multilayer profile of soil with different soil texture and soil density in each layer *i*. Moreover, soil degree of saturation varies with time and depth throughout the profile.

Therefore, thermal diffusivity of soil changes with time and depth for which the transient heat distribution in soil is governed by:

$$\frac{\partial T}{\partial t} = \alpha(z,t)\left(\frac{\partial^2 T}{\partial z^2}\right) + \frac{\partial \alpha(z,t)}{\partial z}\,\frac{\partial T}{\partial z} \tag{1}$$

where $\alpha(z;\, t)$ is the thermal diffusivity of soil which varies with time and space.

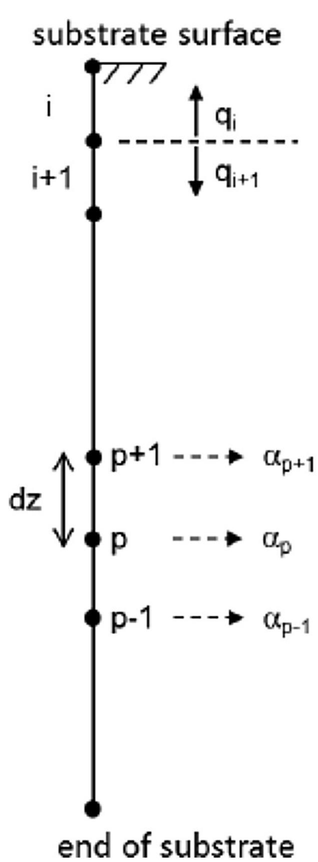

Fig. 1. Node arrangement in the finite difference formulation.

The model is subjected to the boundary conditions:

$$\frac{\partial T}{\partial z}(z = L_\infty) = 0 \tag{2}$$

which shows there is no heat flux at large depth.

$$T(z = 0, t) = T_s(t) \tag{3}$$

where $T_s(t)$ is the measured surface temperature.

Moreover, at the interface between two layers, two boundary conditions must be satisfied. The continuity of temperature:

$$T_i(z = L_i, t) = T_{i+1}(z = L_i, t) \tag{4}$$

and the continuity of the heat flux:

$$-\lambda_i(z = L_i, t)\frac{dT_i}{dz}(z = L_i) = -\lambda_{i+1}(z = L_i, t)\frac{dT_{i+1}}{dz}(z = L_i) \tag{5}$$

Using finite difference method, a series of nodes within the substrate which span from the surface to a defined depth is considered as shown in Fig. 1. For each node *p*, there exists a thermal diffusivity value $\alpha(p)$. At a general node *p*, the differential terms in Eq. (1) can be approximated using the following expressions.

$$\frac{\partial T}{\partial t} = \frac{T_p^{k+1} - T_p^k}{\Delta t} \tag{6}$$

$$\frac{\partial^2 T}{\partial z^2} = \frac{T_{p+1}^k - 2T_p^k + T_{p-1}^k}{\Delta^2 z} \tag{7}$$

$$\frac{\partial \alpha(z,t)}{\partial z}\,\frac{\partial T}{\partial z} = \frac{\alpha_{p+1}^k - \alpha_{p-1}^k}{2\Delta z}\,\frac{T_{p+1}^k - T_{p-1}^k}{2\Delta z} \tag{8}$$

The temporal temperature derivative Eq. (6) is evaluated as the difference between the future time step $k+1$, and the present time step *k*, so that an explicit scheme is obtained. Considering that thermal diffusivities at each time *k* and depth *p* are known parameters; thus, in the finite difference scheme described by Eqs. (7) and (8), thermal diffusivities as well as spatial temperature derivatives are evaluated at time *k* (we have not used a distributed lag model).

The temperature *T* at time $k+1$ is computed in each iteration until the difference of temperature between two iterations becomes less than 10^{-4}. Normally for the convergence, it is enough to have Max $(\alpha(z,t)\mathrm{d}t/\mathrm{d}z^2) < 0.5$ by considering thermal diffusivities at each time *k*, and depth *p*.

The continuity conditions are applied at the interface of each soil layer *i* where the soil textures and dry density of soil changed.

3. Input parameters of the numerical model

This section is dedicated to the model input parameters such as degree of saturation, thermal diffusivity and temperature within depth and time.

3.1. Field description

Since September 2012, a field located in Illkirch, Alsace in France was instrumented with five temperature probes TS_{20}, TS_{21}, TS_{22}, TS_{23}, and TH_{50} and one humidity probe H_S. The field is composed of three in-situ soils: vegetarian soil, wind-blown sandy soil and soil backfill (see Fig. 2).