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A new modeling approach for improved ground temperature profile determination

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ABSTRACT

The knowledge of the ground temperature profile with respect to time and depth is very important in many technological fields like geothermal heat pumps, solar energy systems and geotechnical applications. Many researches were performed in the past in order to evaluate this profile. The most common ones, known as energy balance models, use the energy balance equation as a boundary condition. Unfortunately the performance of these models strongly depends on an accurate estimation of several input factors. The objective of this paper is to develop an improved model for the prediction of the ground temperature profile in which the energy balance equation at the ground surface is supplemented by an empirical correlation for the annual average ground surface temperature calculation. This model is less sensitive to uncertainties of input factors. Furthermore, unlike the previous models, a periodic variation of the sky temperature is introduced instead of a previously assumed constant value. The model is validated against measured data in a site located in Varennes (Montreal-Canada) and two further sites, Fort Collins (Colorado) and Temple (Texas) in the U.S.A.

1. Introduction

The assessment of thermal performance in many engineering applications requires the estimation of the ground temperature as a function of time, location, and depth. Examples of these applications are buried ground heat exchangers connected to ground source heat pump systems or energy storage systems [1,2]. Earth-to-air heat exchangers for heating and cooling of buildings and agricultural greenhouses [3–5] are two other applications. Ground temperature is also important in the design of airport, road pavements, pipelines, as well as for buried high-voltage power cables and nuclear waste disposal facilities. Many factors such as slope orientation, terrain, solar radiation, wind, rain, etc., can affect the ground thermal behavior to a more or less important extent [6] and a reliable assessment approach is highly needed.

Since few measured data are available on ground temperature, several models have been developed for its estimation as a function of time and depth. Determination of this temperature is generally based on the solution of the transient one dimensional heat conduction problem in the ground (Equation (1)), and depends on the type of boundary condition at the ground surface. A full discussion of this subject can be found in Ref. [7]. The boundary condition can take two forms depending on the available data [8]. If the ground surface temperature is known, its temporal variation is the boundary condition. If this information is not available, the energy balance equation can be used as boundary condition at the ground surface. The present work has been performed in this latter context. It is worth noting that, both kinds of boundary conditions lead to solutions of the same general form (Equation (2)) but require different inputs in order to determine their respective parameters.

For a given surface temperature, the most commonly used model is that presented by Refs. [9,10]. More details about this equation including all parameters and variables are given in Ref. [9]. This model seems to be very simple to use. However it requires the knowledge of the ground temperature at or near the surface which is relatively scarce and without it this model cannot be used.

For the surface energy balance models, meteorological data are used in the boundary condition accounting for all heat gains and

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Nomenclature

c_p	specific heat at constant pressure, (J/kg•K)
G	Intensity of solar radiation, (W/m^2)
h	surface convective heat transfer coefficient, (W/m^2•K)
k	thermal conductivity, (W/m•K)
r_h	relative humidity of the air
t	time, (day)
T	temperature, (K)
V	wind velocity, (m/s)
Z	depth of the ground, (m)
Greek symbols	
α	thermal diffusivity, (m^2/s)
α_s	absorption coefficient
σ	Stefan–Boltzmann constant, (W/m^2•K^4)
δ	annual damping depth, (m)
ε	emissivity
ω	angular frequency, (radian/day)
ϕ	phase angle, (radian)
$\dot{\Phi}$	heat flux, (W/m^2)
Subscripts	
Air	air
amb	ambient
dp	dew point
s	ground surface
sky	sky
conv	convection
evap	evaporation

losses over the ground surface [11]. were among the earliest who adopted an energy balance model to investigate the daily and annual variation of the ground temperature in Kuwait. They developed an expression of the ground temperature based on the periodic variation of solar radiation and air temperature, making use of the sol-air temperature definition. Latent heat exchange due to evaporation has not been taken into account in their energy balance equation [12]. reproduced the analysis of [11] by introducing the sol-air-evaporation temperature definition. A parametric study was carried out to investigate the effect of various parameters (air relative humidity, ground absorptivity, wind speed, and evaporation fraction) on the heat transfer in the ground [13,14] presented two other models, very similar to that of [11]. They added another parameter to the energy balance equation which is the latent heat exchange due to evaporation.

A drawback of the aforementioned energy balance models is that their performances depend strongly on the accuracy of the weather data and the estimation of the ground input factors. Many of these input factors are determined by empirical correlations (e.g., convective heat transfer coefficients), some are experimental constants and others are effective mean values (e.g., thermal conductivity and diffusivity of the ground). In addition, while the long wave radiation ($\dot{\Phi}_{sky}$) depends on soil radiative properties, air relative humidity and effective sky temperature it was assumed in the aforementioned models [12–14] to be constant and equal to 63 W/m^2 for all locations in the world. While this value fits conditions on which it is selected and similar conditions elsewhere, it becomes a rough approximation when different conditions have to be considered.

The objective of this paper is to develop an improved model that predicts the ground temperature as a function of depth and time, based on the meteorological data. This model is less affected by the inaccuracy of input factors estimation. The energy balance equation is used as a boundary condition at the ground surface in order to determine the amplitude and the phase angle of the temperature at this location while the annual average ground surface temperature is calculated using an empirical correlation. Unlike previous energy balance models, besides assuming a periodic variation of solar radiation and ambient air temperature, this model assumes a periodic variation of the sky temperature.

2. Model development

The equation describing the transient, one dimensional heat conduction in the ground is:

$$\frac{dT}{dt} = \alpha\frac{dT^2}{dz^2} \tag{1}$$

The ground is assumed to be a semi-infinite medium with constant physical properties. Considering the following initial and boundary conditions:

- $T(z,0) = \overline{T}_s$ at t = 0
- $Ts = T(0,t) = \overline{T}_s - A_s\cos(\omega t - \phi_s)$ at z = 0
- $T(\infty,t) = \overline{T}_s$ at z = ∞

The solution of this problem is given by Equation (2) [8,9].

$$T(z,t) = \overline{T}_s - A_s.\exp^{\frac{-z}{\delta}} \times \cos\left(\omega t - \phi_s - \frac{z}{\delta}\right) \tag{2}$$

This form is used in several software: TRNSYS (2005) [15], DOE-2 (1982) [16] and RETScreen (2005) [17].where:

T(z,t) is the ground temperature at time t (day or hour) and depth z (m).
$\overline{T}_s$is the annual average ground surface temperature, equivalent of the undisturbed ground temperature.
A_s is the annual amplitude of the ground surface temperature.
δ is the damping depth (m) of annual fluctuation of the ground temperature which can be calculated from:

$$\delta = \sqrt{\frac{2\alpha}{\omega}} \tag{3}$$

where α is the thermal diffusivity and ω = 2 π/365 (radian/days) is the angular frequency.

ϕ_s is the phase angle (radian).

At the ground surface (z = 0) the energy balance is applied as a boundary condition (Equation (4)) in order to calculate the parameters $\overline{T}_s$,A_s,φ_s. The details of the energy balance are given in Fig. 1. This figure represents the main heat flux contributions at the surface of the ground including the conduction heat flux into the ground, the convective heat flux transferred between the surface and the ambient air, the short-wave global solar radiation (radiant flux) absorbed by the ground surface, the long wave radiant flux exchanged with the surroundings (sky), and the latent heat flux of evaporation.