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Analysis of the convective heat exchange effect on the undisturbed ground temperature

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Abstract

The ground temperature is an important parameter for several applications such as ground source heat pumps, agricultural greenhouses and ground energy storage systems. This paper describes a numerical model based on 1D transient heat conduction equation, using the energy balance on the soil surface as a boundary condition. The absorbed solar radiation by the soil, the convection heat transfer between the soil and the ambient air, as well as the long wave radiation exchange between the soil and the sky have been considered. An hourly simulation over a whole year (8760 h) with 1 h time step has been conducted using real meteorological data including global solar radiation, ambient dry bulb and dew point temperatures as well as the wind velocity. The model has been validated against measurements and analytical calculations for a site located in Montreal (Canada). The model is applied to investigate the effect of convective heat flux, calculated using three different correlations on the deep ground temperature for different climates. It has been found that in general, McAdams (1954) and Kusuma (2004) correlations can be used for different climates with relatively good agreement between measurements and calculations.

Keywords: Ground temperature; Convection; Heat conduction; Undisturbed ground temperature; Solar radiation

1. Introduction

The prediction of the ground temperature profile is required in various energy applications such as: ground source heat pumps, energy storage, heating and cooling of buildings and agricultural greenhouses. Several works have been done to find a function describing the soil temperature profile. Among all correlations, the most popular one is that proposed by Kasuda and Archenbach (1965). At each certain depth, it gives a sinusoidal variation of the ground temperature about a mean value, as a function of time. The amplitude of the variation decreases with depth at a rate that depends on the properties of the soil until it gives a single value for deep ground temperature. This correlation is used by several softwares such as TRNSYS (2005). Numerous other methods have been proposed to simulate the soil temperature, including numerical methods (Herb et al., 2008; Zoras et al., 2012; Mihalakakou et al., 1995), analytical and semi-empirical methods (Lin, 1980; Droulia et al., 2009; Al-Temeemi and Harris, 2001 and Elias et al., 2004), purely empirical methods (Zheng et al., 1993) and statistical methods that employ intelligent algorithms such as the neural network algorithm (Tabari et al., 2011). It should be noticed that most of these analytical and numerical methods are not

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Nomenclature

a	thermal diffusivity (m^2/s)
C_H	bulk coefficient of the globe
C_p	specific heat at constant pressure (J/kg K)
g	gravitational acceleration (m/s^2)
h	convective heat transfer coefficient (W/m^2 K)
t	time (s)
T	temperature (K)
V	velocity (m/s)
z	depth coordinate (m)

Greek symbols

α	absorption coefficient
ε	emissivity
λ	thermal conductivity (W/m K)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
σ	Stefan-Boltzmann constant = 5.67×10^{-8} ($W/m^2 K^4$)
$\dot{\Phi}$	density of heat flux (W/m^2)

Subscripts

air	air
amb	ambient
c	convective
dp	dew point
g	ground
gs	ground surface
net	net
r	radiative
sky	sky
wind	wind

always able to provide reliable and actual prediction of the ground temperature distribution because of difficulties in the accurate determination of the ground surface boundary conditions and the actual thermal properties of the soil. Other several works have been done based on the energy balance on the ground surface (Khatry et al., 1978; Cellier et al., 1996; Mihalakakou et al., 1997; Mihalakakou, 2002; Thiers, 2008 and Okada and Kusaka, 2013). An explicit expression of the ground temperature as a function of time and depth was derived by Khatry et al. 1978, based on the solar radiation and the atmospheric temperature. The equation was used to investigate the daily and annual variation of the ground temperature in Kuwait. Mihalakakou et al. (1997) and Herb et al. (2008) investigated the effect of the land on the surface temperature by using the energy balance as a boundary condition on the ground surface. Different types of land were considered: bare soil, short and tall grass, a forest and two agricultural crops (corn and soybeans). Thiers (2008) and Mihalakakou et al. (1995) studied the thermal interaction between a building and the ground.

In practice, using simple semi-empirical equations with measurements of the ground surface temperature evolution at a given location is the most popular and credible method for calculating the average ground temperature at a given depth and a day of the year. However, this method cannot be used everywhere due to the fact that the measurement of the ground surface temperature is not available in meteorological data of the site. Indeed, the last category of studies in which the energy balance is applied as a boundary condition at the ground surface is applicable anywhere due to the availability of the required data. However, it constitutes more modeling complexities. As noticed by different studies, the boundary condition at the ground surface consists of three terms including solar radiation, heat losses to the cold sky by long wave radiation and convective heat transfer between the ambient air and the soil surface. The first two terms with all related coefficients are formulized in different references. However several correlations have been proposed to calculate the convective heat transfer coefficient that they all have not been developed for heat transfer between the ambient air and the soil surface. Since the convective heat exchange between the air ambient and the soil surface constitutes an important portion of the overall energy balance at the ground surface, it is important for designers and scientists to be aware of the impact on their calculations. This may give a good sight to choose the appropriate correlation for their works. For example, Mihalakakou et al. (1997) and Thiers (2008) used Mostrel and Givoni's correlation (1982) while Deru (2003), Duffie and Beckman (2006) and Lee and Strand (2006) used McAdams correlation (1954).

Palyvos (2008) also reviewed a large number of convective coefficient correlations with a linear, a power law and boundary layer form. He presented the conditions under which the correlations have been produced. Rabadiya and Kirar (2012) presented a comparative assessment of various correlations and developed an improved equation in the form of experimentally validated correlation for wind loss coefficient. Most of the works cited previously have been conducted for a finite surface, while Kroger (2002) study is among a few works developed specially for an infinite horizontal surface. Based on experimental data, this study developed a correlation for convective heat transfer coefficient between the natural environment and an infinite horizontal surface subjected to a constant temperature or constant heat flux.