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RESEARCH

Numerical analysis for ground temperature variation

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Abstract

This paper aims to predict ground temperature variation with depth for time variant ambient air temperature and solar radiation data for Jamshedpur, India. Finite difference method has been used to discretise computational domain and a scheme has been employed to determine the numerical solution. The numerical results have been validated with experimental measurement of ground temperature. The diurnal temperature variation for the hottest and the coldest days and annual variation for the year 2016 have been computed. The diurnal temperature variation is found up to 0.4 m depth of soil whereas annual temperature variation is up to a depth of 4 m.

Keywords: Numerical analysis, Ground temperature, Diurnal, Annual variation

Introduction

Prediction of soil temperature has important applications such as the passive heating and cooling of buildings and agricultural greenhouses. For the design of earth-to-air heat exchangers, it is necessary to know the ground temperature at different depths. The ambient air temperature and solar radiation are the main meteorological parameters for periodic variation in thermal regime of the soil. Soni et al. (2015) presented an excellent review of research in the area of earth-air heat exchangers. Mathur et al. (2016) and (2017) studied numerically and experimentally on horizontal ground couple heat exchanger.

Chandrakant (1975) studied the ground surface temperature using the heat balance equation and considering with or without soil heat flux. Khatry et al. (1978) and Moustafa et al. (1981) presented ground temperature variation with depth taking into account the periodicity of solar radiation and atmospheric temperature for Kuwait. Bhardwaj and Bansal (1981) calculated daily and annual variations of the ground temperature for dry sunlit, wet sunlit, dry shaded, and wet shaded surface conditions at New Delhi. Mihalakakou et al. (1997) and Mihalakakou (2002) estimated ground surface temperature for bare and short-grass covered soil employing Fourier analysis and validated results by measurements in Athens and Dublin. Paul et al. (2004) performed experimentation analysis of soil temperature of forest area in Australia. Holmes et al. (2008) proposed a new model for the prediction of ground surface and depth-wise temperature difference using ground flux profile. Ozgener et al. (2013) and Chow et al. (2011) measured and predicted the temperature of soil at various depths in Izmir, Turkey, and Hong

Kong, respectively. Kurylyk and Macquarrie (2014) performed analytical solution for estimation of the ground temperature at different weather conditions. Chalhoub et al. (2017) predicted the soil temperature at simple heat and moisture transfer model. Hu et al. (2016) estimates soil temperature, water properties, and soil thermal properties by new Fourier series analytical-based solution. Singh and Sharma (2017) performed CFD modeling of ground temperature variation.

In the present investigation, the temperature variation of soil for dry sunlit condition has been modeled for time varying boundary conditions and compared with experimental data for Jamshedpur, India.

Mathematical formulation

The ground is considered as a semi-infinite solid with one-dimensional coordinates, as shown in Fig. 1a. The variation of ground temperature follows the one-dimensional, transient heat conduction equation given by Carslaw and Jaeger (1980):

$$\frac{\partial^2 T(y,t)}{\partial y^2} = \frac{1}{\alpha}\frac{\partial T(y,t)}{\partial t}. \tag{1}$$

Solution of the above equation is subjected to the first boundary condition at the ground surface given by Bhardwaj and Bansal (1981):

$$-k\left.\frac{\partial T}{\partial y}\right|_{y=0} = h(T_{\mathrm{a}} - T_{y=0}) - \varepsilon\Delta R + \alpha_0 S. \tag{2}$$

The left side of the above equation shows the conduction through the ground surface. The first term on the right-side equation shows convective heat transfer between ground surface ($T_{y=0}$) and air (T_{a}). The second term is thermal radiation (ΔR) with emissivity of

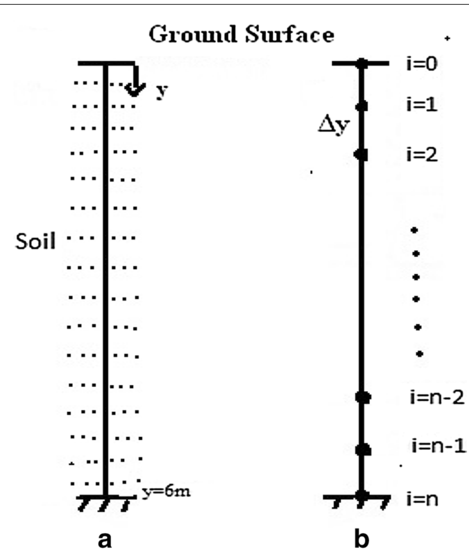

Fig. 1 **a** Physical model and **b** computational domain

soil ε. The third term denotes solar radiation (S) absorbed by the ground surface with an absorptivity of soil α_0. The above equation can be written in the form of general convective heat transfer boundary condition as follows:

$$-k\left.\frac{\partial T}{\partial y}\right|_{y=0} = h(T_e - T_{y=0}). \tag{3}$$

The temperature T_e can be expressed as follows:

$$T_e = T_a + \alpha_0 S/h - \varepsilon \Delta R/h. \tag{4}$$

In Eq. (4), h and ΔR are computed according to Kays and Crawford (1980). The symbol h is the total heat transfer coefficient which includes convective and radiative heat transfer coefficients. The convective term depends on air velocity (v) and radiative term depends on air temperature. ΔR is the thermal radiation which depends on air temperature and sky temperature given in Hillel (1980, 1982, 2004):

$$h = h_c + h_r \tag{5}$$

$$h_c = 2.8 + 3v \tag{6}$$

$$h_r = 4\varepsilon\sigma T_a^3 \tag{7}$$

$$T_{sky} = T_a - 12 \tag{8}$$

$$\Delta R = \sigma[(T_a + 273.15)^4 - (T_{sky} + 273.15)^4]. \tag{9}$$

The second boundary condition is considered as constant temperature which is the annual mean effective temperature ($\bar{T}_e$):

$$T_{y\to\infty} = \bar{T}_e. \tag{10}$$

Numerical analysis

The finite difference method has been employed for discretization of the computational domain, as shown in Fig. 1b. Forward differencing has been used for the time derivative and central differencing for space derivative of the temperature. The explicit scheme has been employed to obtain numerical solution. The discretized one-dimension conduction equation becomes

$$T_i^{j+1} = rT_{i+1}^j + (1-2r)T_i^j + rT_{i-1}^j. \tag{11}$$

The stability criteria is given by Cengel and Ghajar (2011) as following:

$$r = \frac{\Delta t\alpha}{\Delta y^2} \le 0.5, \tag{12}$$

where Δt and Δy are the time step and grid size. The α is thermal diffusivity of the soil.

The temperature variation of the upper surface of the ground is the first boundary condition calculated as follows:

$$T_0^j = \frac{T_1^j + \left(\frac{h\Delta y}{k}\right) T_e^j}{1 + \frac{h\Delta y}{k}}. \tag{13}$$

The effective temperature (T_e) is calculated with hourly data of ambient temperature, solar radiation, and wind speed data using Eq. (4). For the time variant boundary condition, T_e is taken as mean value for each hour ($k = 1,2\ldots$).

The second boundary condition at the end point, i.e., $y = 6$ m is considered as constant temperature which is the annual mean effective temperature ($\bar{T}_e$):

$$T_n^j = \bar{T}_e. \tag{14}$$

Results and discussion

A numerical code based on explicit scheme has been developed in C++. The time step $\Delta t = 60$ s and grid size $\Delta y = 0.01$ m were found optimum by conducting grid sensitivity test. The upper layer of the ground consists of red soil with 20% of moisture content which is assumed to be homogeneous and its physical properties are constant as $k = 1.19$ W/mK, $\rho = 2029.80$ kg/m^3, $c = 756.108$ J/KgK, $\alpha_0 = 0.65$, and $\varepsilon = 0.85$ measured by constant thermal analyser with SH-1 probe. Data for ambient air temperature and solar radiation are measured and available for every minute throughout the year 2016 at Jamshedpur, India [National Institute of Wind Energy (2017)]. The hottest day for the year 2016 is 21st April, whereas the coldest day for the same year is 24th January. Hourly ambient air temperature, solar radiation, and wind speed for the hottest day and the coldest day are shown in Figs. 2, 3, and 4, respectively. The effective temperature

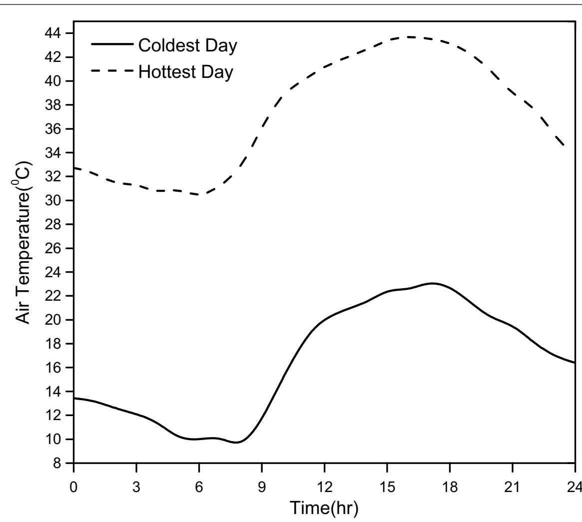

Fig. 2 Ambient air temperature for the hottest day (21st April) and the coldest day (24th January) 2016 in Jamshedpur, India

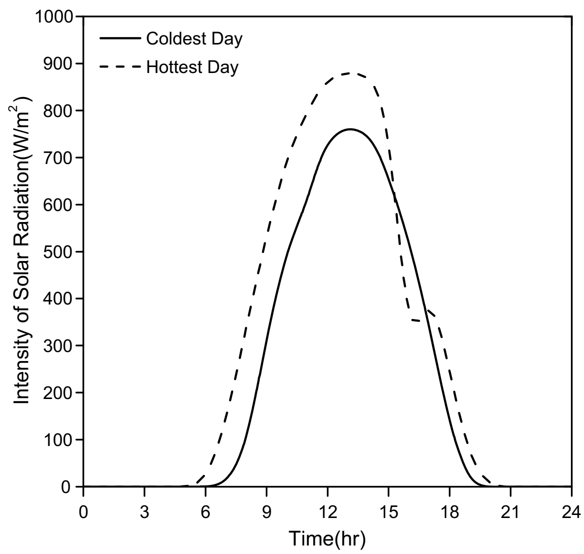

Fig. 3 Solar radiation intensity for the hottest day (21st April) and the coldest day (24th January), 2016 in Jamshedpur, India

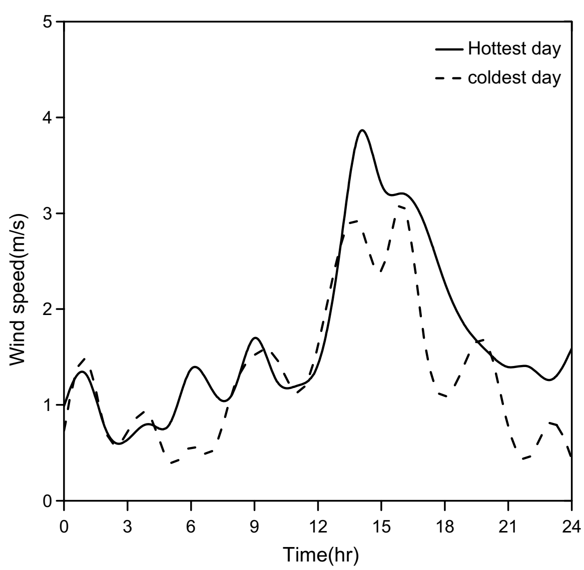

Fig. 4 Wind speed for the hottest day (21st April) and the coldest day (24th January), 2016 in Jamshedpur, India

has been computed for the coldest day, hottest day, and the year 2016 using Eq. (4) and shown in Figs. 5 and 6. The annual mean value of temperature (T_e) is 28.71 °C.

For validation of the numerical scheme, soil temperature has been continuously measured every minute by thermocouples placed at the surface and at 0.5, 1, 2, and 3 m depth of soil. Figure 7 shows the variation of temperature measured experimentally and computed numerically for 6, 12, and 21 h on 29th December, 2016. There is good agreement between experimental and numerical values.

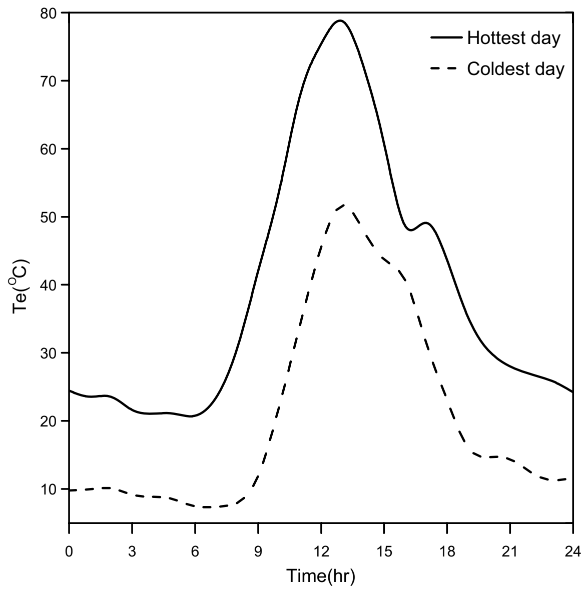

Fig. 5 Temperature, T_e for the hottest day and the coldest day

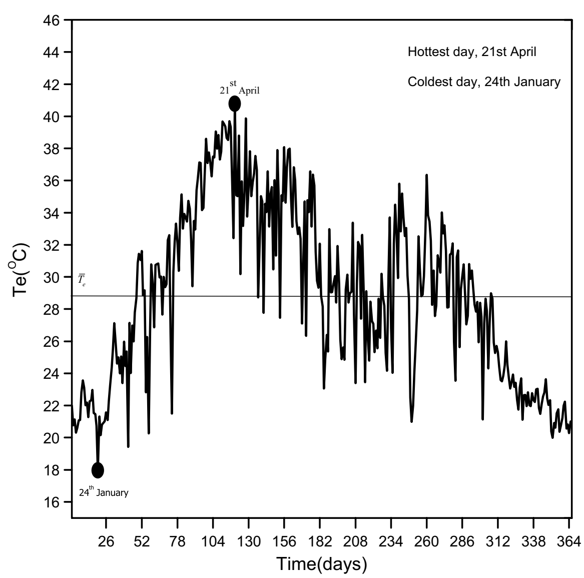

Fig. 6 Temperature, T_e for the year, 2016

Figures 8 and 9 show variation of soil temperature for the hottest and coldest day respectively. As the depth of soil increases, amplitude of temperature decreases. After a depth of 0.4m, there is no diurnal variation of soil temperature.

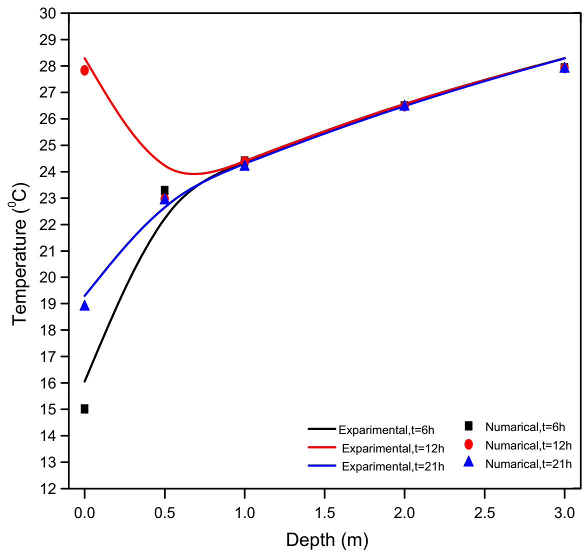

Fig. 7 Variation of soil temperature with depth for 29th December, 2016

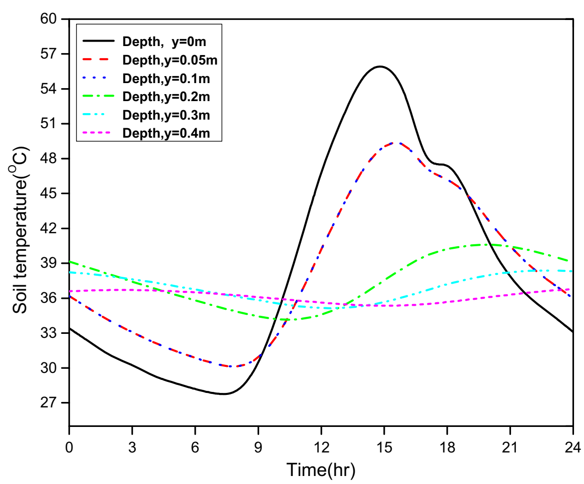

Fig. 8 Variation of soil temperature for the hottest day at various depths

Figure 10 shows annual variation of soil temperature with depth. After a depth of 4 m, the soil temperature becomes constant. Figure 11 shows variation of soil temperature depth-wise for the hottest day and the coldest day. Diurnal variation of soil temperature is up to 0.4 m, whereas annual variation is up to a depth of 4 m.

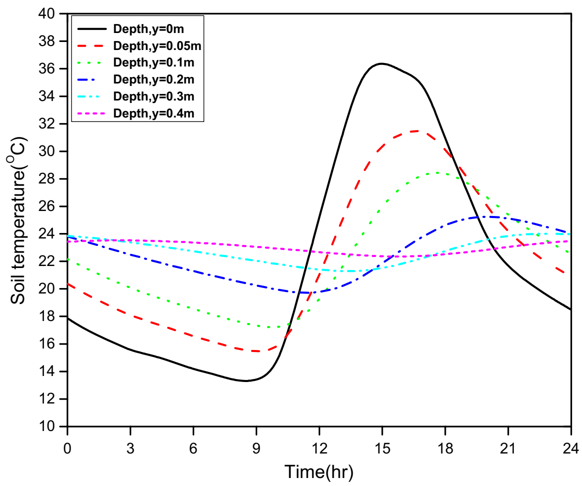

Fig. 9 Variation of soil temperature for the coldest day at various depths

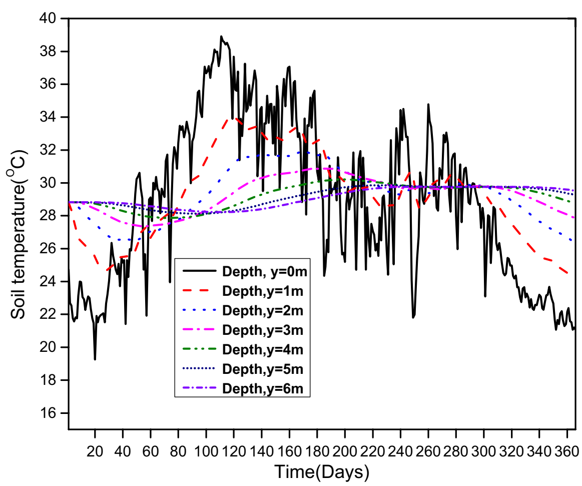

Fig. 10 Annual variation of soil temperature with depth

Conclusions

The present investigation reports the results of soil temperature variation with depth in Jamshedpur, India employing finite difference numerical method which is validated against experimental value. Diurnal variation of soil temperature is found up to depth of 0.4 m, whereas annual variation is up to 4 m of depth.

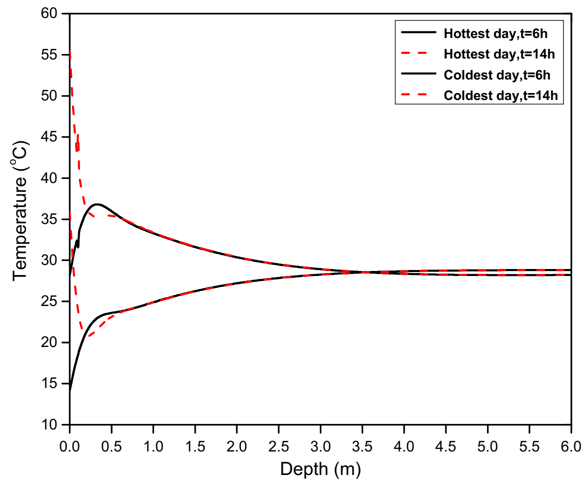

Fig. 11 Variation soil temperature with depth for the hottest and the coldest day

Authors' contributions
Both the authors are equally contribution for the articles. There are no changes in manuscript. Both authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

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