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Sheikh Khaleduzzaman Shah, Lu Aye, and Behzad Rismanchi

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Undisturbed Ground Temperature in Melbourne

Sheikh Khaleduzzaman Shah^{a)}, Lu Aye^{b)} and Behzad Rismanchi^{c)}

Renewable Energy and Energy Efficiency Group, Department of Infrastructure Engineering, Melbourne School of Engineering, The University of Melbourne, Victoria 3010, Australia

^{a)}sheikhs1@student.unimelb.edu.au

^{b)}Corresponding author: lua@unimelb.edu.au

^{c)}brismanchi@unimelb.edu.au

Abstract. The ground surface temperature changes with the diurnal cycle of solar radiation and ambient air temperature. However, the amplitude of the ground temperature variation diminishes with the increase of the depth of the ground and after a certain depth of the ground, it becomes almost constant, where is termed “undisturbed ground temperature (UGT)”. At this depth, the seasonal changes of solar radiation and ambient air temperature changes will no longer affect onground temperature. It is one of the important parameters for designing of the ground heat exchangers and building energy analyses. In this study ground temperatures at various depths in Melbourne were investigated using a 40 m deep borehole instrumented with thermistors. The ground temperatures at various depths (0 m to 40 m) in Melbourne were also simulated by using three methods: Kasuda formula method, simulation (TRNSYS, Type 77), and simplified correlation (developed by Ouzzane et al. in 2015) and the results were compared with the measured data. Root mean square error (RMSE) and mean bias error (MBE) were used to validate and verify the methods. It was found that the estimated ground temperatures at 2, 21, and 40 m depths by Kasuda formula method and simulation (TRNSYS) have the same trends as that of the measured data. The measured annual temperatures of ground at 2 m depth were between 14.7 °C and 19.8 °C, while the temperature at 21 m and 40 m depths remained almost constant. RMSE and MBE of the simulation (TRNSYS, Type 77) were found to be 1.39°C, and -1.39°C respectively compared to measured data at 21 m depth. Based on these values, we conclude that simulation (TRNSYS, Type 77) can reliably predict the ground temperature for the selected site in Melbourne.

Keywords: Undisturbed ground temperature, Borehole, Simulation model, Validation, Melbourne

INTRODUCTION

The information of ground temperature is required for several purposes such as the design of ground heat exchangers of ground coupled heat pump (GCHP) systems and building energy analysis. At the surface layer, the ground temperature is affected by the solar radiation, ambient air temperature and sky temperature. They influence the rate of heat exchange between the atmosphere and the ground [1]. However, the ground temperature varies at the surface zone (up to 1 m from the surface). Further, the temperature variation of a ground decrease in lower depths of ground “shallow zone” (depth of 1 m to 8 m from the surface). At the deeper zone the ground temperature is almost constant which is called “undisturbed ground temperature (UGT)” [2]. According to Kurevija, Vulin [3] UGT is found at a certain depth where seasonal variations in solar radiation and air temperature has no effect.

For a GCHP system, the accurate design of the ground heat exchanger (GHE) is important to avoid the excessive drilling cost or low energy efficiency. Therefore, UGT is one of the most important parameters for sizing GHEs for GCHP or seasonal thermal energy storage (STES) system. Thus, it is essential to accurately determine the UGT of a site, which could be measured directly. To avoid the costly measurements, theoretical model and/or simulation model may be used to determine the UGT based on long-term weather data and thermal properties of the ground. Kusuda and Achenbach [4] developed an analytical model which is widely used for determining the ground temperature. This model has been implemented in several commercial software tools such as TRNSYS [5]. Recently Ouzzane, Eslami-Nejad [2] proposed a simplified correlation to determine UGT, which uses the ambient air temperatures as inputs. Further, Xing and Spitler [6] presented a validated two-harmonic analytical model for UGT based on data of 19 geographically and climatically diverse measurement sites. They found the average of root mean square errors (RMSEs) of the model for all sites were between 1.4 °C

and 2.4 °C at 5, 20, 50, and 100 cm depths. In addition, they have generated a worldwide dataset for UGT by using a model [7]. However, they validated the UGT model for the surface zone (up to 1 m) only.

The analytical formula by Kasuda [4], simulation (TRNSYS, Type 77) [5] and the simplified correlation by Ouzzane et al. [2] may be applied to determine the UGT. The main objective of this investigation is to measure the ground temperatures at various depths on a site in Melbourne then compare with the results from Kasuda formula method, simulation (TRNSYS), and the simplified correlation by Ouzzane et al. (2015)[2]. Three statistical parameters: RMSE, mean bias error (MBE), and Correlation Coefficient (CC) were used for the validation purpose.

METHOD

The value of UGT is required in designing for various applications such as GCHP. Temperature changes in the soil and ground surface are essentially driven by heat fluxes at the ground surface. Various phenomena occurring at the ground surface are presented in Figure 1(a) [2, 8, 9]. The surface temperature (T_s , °C) is raised by absorbing heat from the solar radiation (S , Wm^{-2}). When S reaches the surface of the ground, a part of this flux is absorbed by the ground ($S\beta$) where β is absorption coefficient (-), and the other part is reflected from the surface of the ground. The convective heat (H_{conv} , Wm^{-2}) exchange occurs between the ground surface and ambient air at temperature T_{amb} , (°C). Besides, the surface loses heat by long-wave radiation ($\varepsilon \cdot LW$, Wm^{-2}) due to sky temperature (T_{sky} , °C) where ε is the emittance of ground surface (-). In addition, the surface also loses heat by evaporation (EV , Wm^{-2}) of water. The resultant heat flux (q_{cond} , Wm^{-2}) is transferred into the deeper layer of the ground by conduction.

In this investigation, ground temperatures at various depths (2 m, 21 m and 40 m) were measured and compared with the results from Kasuda formula method, simulation (TRNSYS), and simplified correlation [2]. The locations of the measurements via the borehole at Burnley campus, The University of Melbourne are shown in Figure 1(b). Three thermistors were installed at the depths mentioned to measure the temperatures. A data logger was used to record and store the data every 20 min interval throughout the measuring period (12th April 2017 to 14th March 2018). The analytical model, Eq. (1), developed by Kasuda [4] was used to determine the ground temperatures.

$$T_{GND}(D, t_{year}) = T_{amb} - (T_{amp} \exp(-D \sqrt{\frac{\pi}{365\alpha}}) \times \cos(\frac{2\pi}{365}(t_{year} - t_{shift} - \frac{D}{2} \sqrt{\frac{365}{\pi\alpha}}))) \quad (1)$$

where $T_{GND}(D, t_{year})$ is the ground temperature (°C) at depth D (m) below the surface (0 m) and time of year t_{year} (day). T_{amb} is the annual average ambient air temperature (°C) and T_{amp} is the amplitude of daily average ambient air temperature (°C) annual change. α ($m^2 day^{-1}$) is the thermal diffusivity. t_{shift} refers to the day of the year where the minimum daily average ambient air temperature is found.

The monthly average ambient air temperatures between Jun 2013 and May 2018 recorded [10] at the nearest Bureau of Meteorology Melbourne Olympic Park station (ID: 086338) were applied and this station was 2.6 km away from the study site. The TRNSYS project file used to simulate the ground temperature at various depths is presented in Figure 1(c). Thermophysical properties of ground were estimated based on the average moisture content (16.3 %db) of the soil samples collected by Lhendup (2013) [11] during drilling of the boreholes. The thermophysical properties of clay and water were taken from [12]. The rule of mixtures was applied to estimate the thermal conductivity, density, specific heat of the wet soil (clay and water). From these estimates, the thermal diffusivity of the ground was calculated. The thermophysical properties of the ground at the site and climate information are shown in Table 1.

TABLE 1. Climate data and thermophysical properties

Parameter	Unit	Value	Reference
Annual average ambient air temperature (June 2013 – May 2018)	°C	16.25	[10]
The amplitude of daily average ambient air temperature annual change	°C	5.25	[10]
Time shift (monthly average minimum temperature occurrence)	day	212	[10]
Thermal conductivity of the ground	$W m^{-1} K^{-1}$	1.18	Estimated
Density of the ground	$kg m^{-3}$	1387	Estimated
Specific heat of the ground	$J kg^{-1} K^{-1}$	1344	Estimated
Thermal diffusivity of the ground	$m^2 day^{-1}$	0.0547	Estimated

FIGURE 1. (a) Heat fluxes at the surface on the ground, (b) Schematic diagram of the ground temperature measurement system, (c) TRNSYS studio of ground (GND) temperature.

The simplified correlation, Eq. (2) developed by Ouzzane et al. [2] was used to determine the UGT based on the annual average ambient air temperature.

$$T_{GND} = (17.898 + (0.951 \times (T_{amb} + 273.15))) - 273.15 \quad (2)$$

where T_{amb} is the annual average ambient air temperature ($^{\circ}\text{C}$). Eq. (3 – 5) [13] were used for estimating the statistical parameters (RMSE, BME, CC).

$$RMSE = \left[\frac{\sum_{i=1}^N (Y_i - X_i)^2}{N} \right]^{0.5} \quad (3)$$

$$MBE = \left[\frac{\sum_{i=1}^N (Y_i - X_i)}{N} \right] \quad (4)$$

$$CC = \frac{\sum ((Y_i - Y_{mean})(X_i - X_{mean}))}{\left(\left(\sum (Y_i - Y_{mean})^2 \right) \left(\sum (X_i - X_{mean})^2 \right) \right)^{0.5}} \quad (5)$$

where X_i is the i th measured value, Y_i is the i th simulated (or calculated) value, Y_{mean} is the mean of simulated (or calculated) values, X_{mean} is the mean of measured values and N is the total number of observations. Since the moisture content of the underground soil can have great effects on thermophysical properties, the sensitivity or effects of thermal diffusivity of the ground were investigated for Kasuda formula method at 2 m depth.

RESULTS AND DISCUSSION

The ground temperatures at the minimum and maximum daily average ambient air occurrence dates are presented in Table 2. The ground surface temperature was varied from summer to winter period due to the changes of the ambient air temperature as well as solar radiation. As per measured data, the UGT was found to be 17.6°C at Burnley site, Melbourne. However, in this experiment, the ground temperature was measured at 2 m, 21 m, and 40 m depths only. Therefore, the location of UGT occurrence may be less than 21 m depth, the

exact depth could not be identified because we do not have measurements for the depths between 2 m and 21 m. Hence, further analysis was performed by using TRNSYS (Type 77) simple ground temperature model.

TABLE 2. Measured temperatures (°C) at minimum and maximum daily average ambient air temperatures occurrence dates

Location \ Date	1 st July 2017	28 th January 2018
Ambient air	Minimum daily average, 7.48	Maximum daily average, 32.89
At 2 m depth	16.78	18.84
At 21 m depth	17.63	17.62
At 40 m depth	17.70	17.64

Figure 2 shows the temperature profile of ground at various depths based on measured, Kasuda formula method, and simulation (TRNSYS). The data gaps in the curves are for the duration the measured data are not available (14th March to 12th April). It was found that Kasuda formula method and simulation (TRNSYS) data are the same at 2 m, 21 m and 40 m depth since TRNSYS (Type 77) used Kasuda formula. Therefore the temperatures for measured, and simulation (TRNSYS) are shown in Figure 2. The simulation (TRNSYS) followed the same pattern of measured data at 2 m depth. The average UGT was found to be 17.64, and 16.25 °C at 21 m depth for the measurement, and simulation (TRNSYS) respectively. The average UGT was found at 17.68, and 16.25 °C at 40 m depth based on measurement, and simulation (TRNSYS), respectively. The deviation of UGT was found 1.39 °C at 21 m depth in between measured, and simulation (TRNSYS) because of ambient air temperature is the most influential parameter to determine the UGT by simulation (TRNSYS) where the value of annual average ambient air temperature was found low. It was found that the measured temperature values have a very minor difference in between 21 m and 40 m depth, and they are within measurement accuracy of the thermistors. However, the UGT calculated by the simplified correlation [2] was found to be 19.97 °C. The deviation was found to be 2.28 °C.

FIGURE 2. Monthly average ambient air temperature and ground temperature profiles (Burnley, Melbourne)

However, for the local site (Burnley, Melbourne) variation in average ground temperature (ΔT_m , °C) was found to be 1.4 °C between TRNSYS and measured at 21 m and 40 m depths as shown in Figure 2. As described the various heat fluxes (Figure 1(a)), the ground temperature is highly influenced by the ambient air temperature as per different UGT equation models [2, 9] where other heat fluxes were almost cancelled out by each other. In addition, Baggs [14] investigated on remote prediction of ground temperature in Australia soil. The measured UGT was found to be 1.8 °C higher than the annual average air temperature in New South Wales. The values for RMSEs and MBEs are presented in Table 3. The maximum RMSE was found for simplified correlation and minimum at simulation (TRNSYS) at 2 m depth.

TABLE 3. Statistical parameters of the models/formula compare to measured values

	2 m depth		21 m depth		40 m depth	
	TRNSYS Type 77	Simplified correlation	TRNSYS Type 77	Simplified correlation	TRNSYS Type 77	Simplified correlation
RMSE (°C)	1.03	2.89	1.39	2.33	1.43	2.28
MBE (°C)	-1.01	2.89	-1.39	2.33	-1.43	2.28

As per RMSEs and MBEs at 21 m and 40 m depth of the TRNSYS simulations (Figure 3), it could be concluded that there are negligible effects of thermophysical properties of ground on UGT. However, ground temperature was found affected by thermophysical properties at 2 m depth (Surface zone). Therefore the effects of thermal diffusivity of ground at 2 m depth on statistical parameters were investigated (see Figure3). It was found that there is a thermal diffusivity value which provides the minimum RMSE or the maximum CC. The minimum RMSE was found 1.03 °C where maximum CC was found 0.99 at 0.045 and 0.055 m² day⁻¹ thermal diffusivity. However, MBE was found decreased with the increase of thermal diffusivity of the ground. The MBE was found to be -1.00 and -1.01 °C for 0.045 and 0.055 m² day⁻¹ thermal diffusivity respectively.

FIGURE3. Effect of thermal diffusivity of ground on the ground temperature at 2 m depth.

Figure 4 shows the monthly ground temperature variations with various depths. Simulation (TRNSYS) was used to determine the ground temperature at 0, 3, 6, 9, 10, 11, 12, 13, 14, 15, 18, 21, and 40 m depth on the representative dates [15] of every month (from January to December). At 0 m depth, the maximum ground surface temperature was found to be 21.38 °C in January and the minimum ground surface temperature was found to be 11.15 °C in July. However, it was found that the UGT is 16.25 °C which begins from 12 m depth of the ground where the maximum variation of UGT is 0.09 °C in between summer and winter period at 12 m depth. However, the measured UGT was found to be 17.6 °C which is higher than the simulated value (16.25 °C). It should be noted that Type 77 or Kasuda formula considers ambient air temperature only, not the effect of ground heat flux. The measured UGT at 40 m depth is slightly higher than that of 21 m depth. The value of UGT at 21 m is higher than the annual average ambient air temperature. The variations of temperatures at specific depths are presented in Table 4.

FIGURE4. Monthly ground temperature Vs ground depth at Melbourne.

TABLE 4. UGT variation at specific depths

Depth (m)	0	3	6	9	10	11	12	13	14	15	18	21	40
Temp.variation (°C)	10.23	3.17	0.94	0.29	0.19	0.13	0.09	0.06	0.04	0.03	0.01	0.0	0.0

CONCLUSIONS

The UGT on site in Melbourne was analysed based on measured, Kasuda formula method, simulation (TRNSYS), and simplified correlation[2]. The average UGT was measured to be 17.64°C and estimated to be 16.25 °C at 21 m depth by TRNSYS, Type 77. However, the UGT was estimated to be 19.97 °C by the simplified correlation[2]. To compare the data, statistical parameters such as RMSE, and BME were used to validate TRNSYS Type 77. Further, it was found that the thermophysical properties have no effect on the UGT. However thermal diffusivity has an effect on ground temperature at 2 m depth. As per simulated results it was found that the UGT begins from the depth of 12 m in Melbourne.

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