Theoretical and Experimental Estimation of Soil Temperature Distribution in Arid Region

S E Younis¹, K S Shibib¹ and M A Munshid²

¹Laser and optoelectronics engineering Department-University of Technology-Iraq
²Al-Mamoon University Collage

E-mail: 140008@uotechnology.edu.iq

Abstract. In this work, the one-dimensional finite element solution of the transient heat equation was used to calculate the temperature distribution through the soil in the arid region. As an example, Baghdad city was chosen due to the dryness of its weather which can be regarded as an arid region. The solar radiation, ambient temperature, relative humidity, soil thermal properties, soil water content, and wind speed were used as input parameters to the solution to obtain the surface and in-depth temperature distribution in the soil. The solar light components that hit the soil have been obtained theoretically and measured experimentally with good nearby results. The obtained temperature distributions were compared with experimental data and good nearby results could verify the used methodology.

1. Introduction

Even a small part of the solar radiation is reaching the earth, it controls the basic living phenomena on the earth. Sun saves the acceptable limit of the earth's surface temperature together with the temperature of the environment. Soil temperature is the main parameter that affects plants and micro-organisms that lived in the soil. The activity of decomposed micro-organism increases by the increase in soil temperature. The growth rate of micro-organisms and plants increases two- or three-fold with an increase of 10 °C up to 30 °C.

On the other hand, the most important parameters in studying the underground effect on installation are the soil temperature. The determining of soil temperature is important in order to calculate the heat that could exchange between earth and building also the wide use of buried fiber optics in communications has made this topic as a matter of importance. Another importance in calculating surface and in-depth earth temperature distribution is the laying of electrical cable through the ground away from the accidental action that could damage the cable and maintain moderate surrounding temperature to reduce loss. The soil temperature is also important for many activities including agriculture, horticulture, and even for underground water hydrology [1].

Many previously published papers studied the possible temperature distribution and an in-depth of the ground in many locations. Chalhoub et al. [1] derived a model to predict transient heat and moisture transfer in the soil under moderate climates and obtained the surface ground temperatures using a minimum set of variables and weather information. Krarti et al [2] suggested an analytical model that predicts the annual variation of soil surface temperature from readily available weather data and soil thermal properties with a 10% error. Al-Timimie et al. [3] used thermal images from the satellite to determine the soil temperature in Iraq during a certain period. Hasan [4] measured the temperature distribution inside mud-sand mix ground that partly shaded through summer season at Baghdad city and one of his findings was that the average temperature at 1.6 m depth is approximately 24 °C. Abbas et al [5] studied the variation of soil temperature with time and depth in the Karbala region (88 km southwest from Baghdad) where a one-dimensional mathematical model was proposed to study the annual soil temperature variation. They found that at a depth below about six meters the soil temperature is approximately constant and equal to 24 °C.
In this work, a transient one-dimensional heat equation was used to obtain the temperature distribution through the soil in Baghdad using the finite element method. The solar radiation, ambient temperature, relative humidity, soil thermal properties, soil water content, and wind speed were used as input data to the solution to obtain the surface and in-depth temperature distribution of the soil. All input data were measured practically and compared with theoretical data when available. The obtained temperature variations were compared with experimental data and good nearby results verified the used methodology.

2. Theory:
2.1 Partial differential equation and boundary conditions
A transient one-dimensional heat equation could satisfy the mechanism of heat transfer to, from, and through the soil. The varying boundary conditions that imposed on the soil can be simulated as follow:

2.1.1 Solar heat radiation
Earth is exposed to solar radiant which results in heat that is absorbed and reradiated by the ground. It is assumed that all solar radiation incidents on the ground become heat gain except the portion that is reflected at the surface. The ground absorptivity is taken to be 0.83 [6], assume the induced heat to the ground is equal to that direct fallen on the ground plus the diffused solar radiation, then the induced energy to the soil surface is [7-8]:

\[ I_s = \alpha_d (I_{DN} \cos \theta + I_d) \]  

Where

\[ I_{DN} = A e^{\sin \beta} \]  

(1a)

\[ \alpha_s = 0.83 \]  

(1b)

\[ I_d = I_{DN} C = I_{d,H} \]  

(1c)

\[ A, B, \text{and } C \text{ are referred to constants depending on the location of the studied region [7-8]. Many references establish the criteria for calculating the azimuth angle } \gamma \text{ and angle of the sun } \beta [7-8]. \text{ and also } I \text{ refer to power intensity (W/m}^2\text{), } \alpha \text{ is the absorptivity. DN and d, H refer to direct normal and horizontally diffused respectively. also } I_d \text{ refer to diffused solar intensity. s- refer to the surface , I, refer to the absorbed energy} \]

A computer program was created to calculate these angles at each hour in the day through the year in order to determine the part of solar energy induced to the soil at each hour in solar time at latitudes of 32.2, assume solar time is converted to local time based on reference [8]

2.1.2 Thermal radiant heat transfer
A well-defined linearized radiation coefficient is[8]

\[ h_r = 4 \varepsilon_s \sigma \left( \frac{T_s + T_{sky}}{2} \right)^3 \]  

(2)

the surface emissivity \( \varepsilon_s = 0.92 \times 10^{-4} T_{sky}^2 \) [8]  

(2a)

For simplicity, a reliable value of sky temperature is as used by the Blast program [9-10] which is equal to environment dry bulb temperature minus 6 K. Instantaneous sky temperature \( T_{sky} \) is used to determine thermal radiant heat transfer using effective sky temperature that seems to affect the amount of reradiating energy as follow:

\[ q_{rstrad} = h_r (T_{sky} - T_s) \]  

(3)

assume \( T_s \) is refer to surface temperature.

2.1.3 Convection heat transfer
The external convective heat transfer coefficient between air and soil was found experimentally by Garzoli et al. depending on wind speed [11]:

\[ h_g = 7.2 + 3.8 V_o \text{ W/m}^2\text{.K} \]  (4)

Where \( V_o \) - the wind speed (m/s). It is worth to mention that the common wind direction in Iraq is a north-west wind with a common velocity of 4 m/s, then one can obtain the convection heat transfer from or to the soil as follow:

\[ q_{co} = h_g (T_\infty - T_s) \]  (5)

where \( T_\infty \) is the environmental temperature \(^\circ\text{C}\) and \( T_s \) refer to surface soil temperature (\(^\circ\text{C}\))

2.1.4 Heat due to Evaporation (\(E_v\)); The estimation of the heat flow during evaporation from surfaces is a complicated process. Several authors have developed models to calculate the evaporation rate from the soil as a function of meteorological conditions. The heat flow due to evaporation from the soil surface which can be evaluated by the following equation [12]

\[ E_v = 0.0168w h_g [(aT_s + b) - r_a(aT_\infty + b)] \]  (6)

Where \( E_v = 0.0168w h_g (aT_s + b) \) and \( E_\infty = 0.0168w h_g r_a(aT_\infty + b) \) are ...

and \( w \) is soil water content, \( r_a \) is the relative humidity of the air just above the soil surface and \( a = 103 \text{ Pa/K} \) and \( b = 609 \text{ Pa/} \) for moderate temperatures. The water content of the soil is 0.2 in Nov. - April, this means that evaporation occurs could not occur in the remaining months.

2.1.5 Variation of environmental conditions

The variation of daily temperature program is published by Parton [10] which needs some local temperature extremes. It needs the hour, after the noon of the sun, to reach the maximum temperature which is known in Baghdad to be after 3 hours from the noon of the sun also this program needs the time in hours after sunrise to reach the minimum temperature which is known to be zero.

2.2 Surface boundary condition formulation

The surface equation of heat transfer can be summarized as

\[ q_s = I_i \pm q_{co} - q_{rad} - E_v \]  (7)

and \( q_{rad} \) is described in Eq. (3).

2.3 Soil thermal properties

Samples of soil from different depth were collected and their density, specific heat, thermal conductivity and water content were measured and their average values for dry soil were found to be; Density(\( \rho \))=1600 kg/m3, specific heat (\( C_p \))= 800J/kg.K, thermal conductivity(\( k \)) =0.25 W/m.K, Taking into account wet soil, the water content plays an effect on thermal properties mentioned above where water content was measured and its average value was found to be approximately equal to 0.2 in rainy months (Nov, Dec., Jan., Feb, Mar.and Apr.)[13]. A good assumption is to find a relation between thermal conductivity, water content and bulk density as suggested by reference [14] and was used here.

2.4.Finite element Formulation

The modelling of heat transfer equation subjected to the boundary conditions mentioned above can be achieved using Least square discretization where the studied region \( \Omega \) is divided into a number of several elements, \( \Omega' \), with linear shape function \( N_i \) associated with each node, the unknown temperature \( T \) can be presented through the domain at time \( t \) by

\[ T = \sum N_i (x,t) T_i(t) \]  (8)
where \( T_i(t) \) are the nodal temperatures. Substitution of the above equation into the heat transfer equation and application of the Galerkin method results in a system of ordinary differential equations having the form of [15];

\[
[C] \dot{T} + [K]T + [F] = 0
\]

(9)

where \( \dot{T} = \begin{bmatrix} \frac{\partial T_1}{\partial t} \\ \frac{\partial T_2}{\partial t} \\ \vdots \\ \frac{\partial T_p}{\partial t} \end{bmatrix} \), \( T = \begin{bmatrix} T_1 \\ T_2 \\ \vdots \\ T_p \end{bmatrix} \) and \( [F] = \begin{bmatrix} F_1 \\ F_2 \\ \vdots \\ F_p \end{bmatrix} \) \( p \) is the total no. of the node (9a)

and the typical matrix elements are

\[
K_{ij} = \sum_{\Omega'} \int_{\Omega'} k_{ij} \left( \frac{\partial N_j}{\partial x} \frac{\partial N_j}{\partial x} \right) d\Omega' + \sum_{\Gamma'} \int_{\Gamma'} N_j \left( h_\omega + h_r + E_s \right) d\Gamma'
\]

(10)

\[
C_{ij} = \sum_{\Omega'} \int_{\Omega'} \rho C_p N_j N_j d\Omega'
\]

(11)

\[
F_i = -\sum_{\Gamma'} \int_{\Gamma'} N_j (I_i - h_o T_\infty - h_r T_{sky} - E_\infty) d\Gamma'
\]

(12)

Here \( E_s, E_\infty \) are the components of evaporation loss that related to soil temperature \( T_s \) and environmental temperature \( T_\infty \), see Eq.(6).

The sum is taken over the contribution of each element, \( \Omega' \) and \( \Gamma' \) refers only to the element with external boundary on which surface condition is applied, using linear shape function which normalizes to a time interval \( \Delta t \), the result is in a matrix form of

\[
\left( \frac{[c]}{\Delta t} + \Theta[K] \right) \tilde{T}_{n+1} + \left( \frac{-[c]}{\Delta t} + (1 - \Theta)[K] \right) \tilde{T}_n + \tilde{F} = 0
\]

(13)

where

\[
\tilde{F} = \tilde{F}_{n+1} + \tilde{F}_n (\Theta - 1)
\]

(13a)

\( \Theta \) can have a different value. In this solution, a forward difference has been chosen due to its simplicity (i.e. \( \Theta = 0 \)) and an iteration solution was used at each time step \( n, n+1 \) to ensure precise results. A time step of 1 Hr was chosen and a starting time on the 1st of March with an initial temperature of 22.5 °C (i.e. the annual average temperature of the weather). In the program, the results are not recorded until the next year (i.e. at the next first of January) where the environmental boundary conditions take sufficient time to affect correctly the result.

3. Result and discussion
A program based on the finite element approach was made to obtain the hourly based temperature distribution through the ground. A good starting value of the initial temperature distribution on 21 March was assumed to be equal to the annual environmental average temperature. The program was run without recording any temperature till the next first of January, this is to ensure that the boundary conditions, physical and thermal properties of soil take sufficient time to show their effect on the result. Horizontal components of direct normal solar radiation plus the diffused solar radiation were measured using a detector and calculated where the very good nearby result was obtained, as shown in Fig 1. The max. error in readings was found to be less than 4%. The water content of the soil was measured by weighing soil before and after drying and it was found to be equal to 0.2 in Nov.- April and it is assumed to be
about zero at other months, this value of water content is also as predicted by reference [13]. This recalls that the evaporation heat that is modelled in Eq. (6) is only available in those months. The ambient temperature through a day was assumed to have a pattern close to what really occurs which was suggested by a program suggested by Parton [10], where the maximum temperature occurs three hours after the noon of the sun, while the minimum temperature occurs at the sunshine. The maximum and minimum temperature and relative humidity through a day (one average through the month) were taken from a weather center that published these data in Baghdad. The temperature variation that causes heat transfer by convection together with sun-induced sun radiation, the reradiating energy, and evaporation loss from soil composed the varying boundary conditions that affect the surface and in-depth temperatures of the soil. Their effects are shown in Fig 2-5 where the soil thermal properties play an important role in affecting the temperature distribution. Figures 2-5 show experimental and theoretical temperature distribution through the soil at different depths on 21 March, June, Sep. and December. Assume a thermocouples type T was used to measure temperatures after they were calibrated with boiling and freezing pure water. The good nearby result confirmed the used methodology where the maximum difference between theoretical and measured values was found not to exceed 3%. It is observed that through those months, the maximum soil temperature occurs at 3 p.m. on 21 June where it reaches approximately 6 °C while the minimum temperature at that month reaches 24 °C and the minimum temperature occurs when the sun rises at 21 Dec with a value of 6 °C, as shown in Fig 5. Figure 6 shows the theoretical and experimental daily average temperature at different depths with good nearby result where the average surface temperature of the soil reaches its minimum value in

![Figure 1: Solar light intensity on a horizontal surface on 21 March (continuous line), 21 June (short dashed line), 21 Sep. (long dashed line), 21 Dec.(dashed-dot line), plus sign indicates experimental measurements](image)

The oscillating in temperature is damped out as the depth increased also the peaks in minimum and maximum were shifted to the daytime, this is due to the low thermal diffusivity of the soil. Of course, one may expect that the oscillating and peaks may increase as the thermal diffusivity increased (i.e. in stony or sandy soil).
Fig. 2. Temperature distribution through the soil on 21 March, Dashed dot line is the environmental temperature, small dashed is the surface temperature, large dashed at depth of 10 cm, the thin line at depth of 50 cm, and the bold line at depth of 8 m. plus sign indicates experimental measurements.

Fig. 3. Temperature distribution through the soil on 21 June, Dashed dot line is the environmental temperature, small dashed is the surface temperature, large dashed at depth of 10 cm, the thin line at depth of 50 cm, and the bold line at depth of 8 m.
Fig. 4. Temperature distribution through the soil on 21 Sep., The dashed dot line is the environmental temperature, small dashed is the surface temperature, large dashed at depth of 10 cm, the thin line at depth of 50 cm and the bold line at depth of 8m.

Fig. 5. Temperature distribution through the soil on 21 Sep., The dashed dot line is the environmental temperature, small dashed is the surface temperature, large dashed at depth of 10 cm, the thin line at depth of 50 cm, and the bold line at depth of 8m.
4. Conclusions

The finite element method was used successfully to predict the temperature distribution through the soil in an arid region such as in Baghdad city. A computer program was created to obtain the temperature distribution in the soil. The sunlight component has been measured and calculated theoretically based on ASHRAE standard with a good nearby result where it was used together with environmental conditions and evaporation loss from soil (if any) to predict the temperature distribution in the soil where its thermal properties were measured which were also used as input data to the program. The theoretically calculated temperature distributions were compared with the measured values and good nearby results were found. It was observed that the maximum temperature of soil could reach 65 °C on 21 June and the minimum temperature reaches about 6 °C at the sunrise on 21 December. It is also observed that the oscillating in temperature decreased as the depth increased. With correct input data, the program was tested to obtain good nearby results compared with that measured practically.

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