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Modeling the soil surface temperature for natural cooling of buildings in hot climates

Mohamed Derradji [a,*], Messaoud Aiche [a,†]

[a] *Department of Architecture, Faculty of Architecture and Town planning, University of Constantine 3, Algeria*

Abstract

The soil has the potential to serve as a cooling source for buildings. However, the unavailability of data concerning the thermal behavior of the ground limited the widespread of underground cooling systems. These last years, the concept started to obtain an attention because of the results of some studies indicating that the development of such systems could present an alternative for the cooling and the natural ventilation of buildings. Coupling solar chimneys with buried cooling ducts was investigated as a method of appropriate design for cooling and natural ventilation in hot climates. The modeling of the proposed device was developed and presented in a previous scientific meeting. The value of the ground temperature was assumed. In this work, a method of evaluation of the ground temperature according to the depth and the treatment of the ground surface is presented. In addition, the work intends to show the importance of the potential of the thermal mass of the ground for cooling buildings. The method is estimated on the basis of weather data. The results of this study indicate that if irrigation is applied to the soil surface in summer the ground offers a good source of cooling for buildings. A decrease in temperature to 18°c was noted between the soil temperature at a depth of 1m and the ambient outside temperature.

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Keywords: Modeling, soil temperature, underground cooling, natural ventilation.

* *Corresponding author:*
* Mohamed Derradji. Tel.: 075317005; *E-mail address:* derradjimed@gmail.com
† Messaoud Aiche. Tel.: 0558999465, *E-mail address:* aichmessaoud@yahoo.fr

1. Introduction

In an earlier paper a proposed design of solar chimneys coupled with buried cooling ducts was investigated and a

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developed mathematical model was presented [1].The preliminary results of the study simulated a simple configuration (one solar chimney coupled with one cooling buried duct), showed that the design configuration of the device is not effective to provide the required conditions of ventilation and passive cooling. To achieve the objectives of the investigation, a design of an improved device has been proposed. The developed design is based on multiplying the number of solar chimneys and cooling buried ducts Fig. 1. The improved analytical model can determine the temperature of space based on data concerning the site of the project (such as the ambient air and the soil temperature), the number of occupants, the type of activity and the number of elements constituting the studied system (number of solar chimneys and cooling buried ducts). The value of the ground temperature in the mathematical model was initially assumed. As the value of the ground temperature varies according to a number of parameters the purpose of this work is to present a method of evaluation of the ground temperature according to the depth and the treatment of the ground surface. In addition, the work intends to show the importance of the potential of the thermal mass of the ground for cooling buildings.

2. The potential cooling of the soil's thermal mass

The ground is regarded as a large reserve of solar energy. Its heat capacity is so important that the diurnal variations of the surface soil temperature do not penetrate more than 0.5m, and seasonal variations not more than 4.0m in-depth. Beyond this depth, the temperature of the ground remains constant. The value of this temperature is usually considered equivalent to the annual average solar temperature of its surface [2].

The mass of the ground in lower part around, and sometimes also above a building can be useful in the majority of the climatic areas like a source of natural cooling for the building, in a passive or active way. In summer, with a depth of a few meters, the temperature of the ground is always below the average ambient temperature, and is particularly below the temperature of the air during the day. As a result, the soil has the potential to serve as a cooling source for buildings. Furthermore, it is possible by very simple means to lower the temperature of the earth well below its normal temperature. The cooling surface, where the temperature of the soil surface is lowered, induces a significant reduction in the temperature of the mass of earth which is below the surface.

Nomenclature

A	Cross section (m)
ρ	Density of air
g	Gravity (m/s2)
r	Duct radius (m)
t_s	Surface temperature (°C)
m	Mass flow rate (Kg /s)
t_e	Bulk earth temperature (°C)
Cp	Specific heat (wh/Kg°C)
K	Thermal conductivity
h	Thermal transfer coefficient de (w/m².K)
l	Length of duct (m)
t_i	Inlet air temperature (°C)
t_o	Outlet air temperature (°C)

Greek Symbols

β	Variable of integration
α	Thermal diffusivity of soil (m/s)
τ	Small interval of time (s)

Indeed the protection of the ground surface by a layer of gravels from the solar rays makes it possible to cool the soil while allowing evaporation. In arid regions, the difference between the maximum temperatures of the outside ambient air and the cooled temperature of the earth at a depth of one meter may attain 15°C in mid-summer season [3]. The temperature of the ground surface is characterized by broad diurnal and annual variations, which are determined by the absorbed solar energy and the temperature of the ambient air. The range of daily surface temperature is usually larger in summer, especially in arid regions, when the solar radiation impinging on the surface is higher. It is shorter in winter, mainly in cold regions.

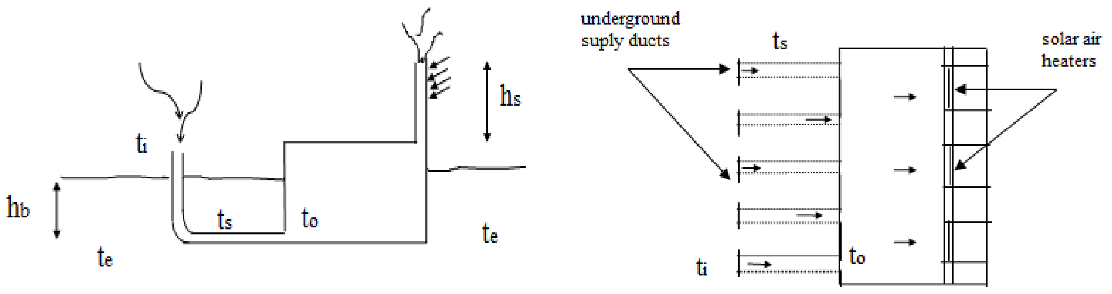

Fig. 1. (a) The investigated design (air heater coupled with an underground cooling duct); (b) Layout of the multiple systems (a number of solar air heaters coupled with a number of underground cooling ducts)

3. The thermal model of an earth cooling duct

To predict the variation of air temperature along the buried duct some basic principles of heat transfer should be taken into account. Under a transient heat transfer mode the main equations which were used to predict the variation of air temperature at any point of the buried ducts were:

$$t_o = \frac{t_i.(m.cp - hA/2) + h.A.t_s(i,j)}{m.cp + h.A/2} \quad (1)$$

$$Q = m.cp.(t_i - t_o) \quad (2)$$

$$t_{s(i,j+1)} - = t_e + \frac{Q}{2\pi.K.l}\int_{rn}^{\infty} e^{-\beta^2}.\beta^{-1}.d\beta \quad (3)$$

With:

$$n = \frac{1}{2}\sqrt{\alpha.\tau}$$

In solving for the air temperature along the duct length, the bulk earth temperature te, was assumed and the initial surface temperature (when j=1) was assumed to be equal to the bulk earth temperature [4]. In the light of a number of experimental and analytical works [5, 6] and [7], the bulk earth temperature could be calculated.

On the surface, the average temperature of the ground is determined by the type of the local climate, which can change year by year, and by balance between several modes of thermal transfer i.e.; the absorption of the incidental solar radiation, the heat loss of long waves radiation towards the sky, the heat exchange by convection with the ambient air and the heat loss by evaporation from the soil's surface. Moreover, with suitable treatments the temperature of the ground surface can be raised or lowered above or below the normal temperature of the ground. The change in surface temperature also affects the soil temperature at depth.

3.1. Mathematical modeling of the natural ground temperature

Soil temperature undergoes a daily cycle, and an associated cycle with the weather variations in addition to one annual cycle. These variations are restricted to the layers close to surface. The daily cycles are felt with a penetration depth of approximately 0.5m under surface and the weather cycles, of approximately 1m [6].

To evaluate the temperature of the ground, the soil is regarded as a semi-infinite solid. It is expressed according to the depth and time. When the surface temperatures are known, the soil temperature to a given depth can be estimated. If these data are not available, weather data can be used in a limited state which indicates the energy balance at the soil surface [8].

In order to evaluate the temperature of the ground, several mathematical models were developed such as those of Morland [8], Kusuda [9], and Labs [10]. Their models present a solution of the equation of heat transfer of a semi-infinite solid whose variation in the external temperature is sinusoidal.

$$T_{Z,t} = T_m - A_s.\exp^{(-Z/365a)}.Cos[(2/365).[t - t_d - (Z/2)(365/a))^{1/2}]] \quad (4)$$

Where:

$T_{z,t}$ Temperature of the ground to a depth Z and the day T
T_m Annual average temperature on the ground
A_s Annual surface temperature amplitude of the ground
t Period of the year in days
t_d Date of the minimum surface temperature
a Thermal diffusivity of the ground

The inconvenience of this formula is its dependence of the annual amplitude of the soil's surface temperature, and its diffusivity. Data of annual amplitude of the ground surface are not usually available, and the question of the effective diffusivity of the ground is complex. Without these data this formula cannot be employed. On the basis of experimental study undertaken in several climatic areas, Givoni recapitulated his results in a simplified method [3]. It makes it possible to estimate the soil's temperature according to the weather data of the site, the range damping factor F and the time lag L defined by the formula:

$$T_s = T + A_o.\exp^{(-F.Z)}.Sin(0.986.N - 125 - L.Z) \quad (5)$$

Where:

T_s Soil temperature on day N at depth D; (°C)
T Annual average of the soil's temperature (°c)
F Range damping factor depends on climate and soil type.
Z Depth under surface; (meters)
L Time lag per meter depth depends on climate and soil type; (days)
A_o Annual amplitude of the soil's surface temperature (annual range /2); (°C)
0.986 Days of the year expressed in degrees (360/365)
N Day number (January st =1)
125 April 25. According to the experimental observations, the 25th of April is selected as being the day in which the maximum of surface temperature is reached.

The values of the damping factors F, and the time lag L, are given in tables 1 and 2.

Table 1. Damping factor (F) for different climates and soil types [3] p.233.

	Soil type		
Climate	Loam / clay	Intermediate	Sandy
Desert	0.45	0.50	0.55
Arid	0.40	0.45	0.50
Intermediary	0.35	0.40	0.45
Humid	0.25	0.35	0.40
Wet	0.20	0.30	0.35

Table 2. Time lag (L) for different climates and soil types [3] p.234.

	Soil type		
Climate	Loam / clay	Intermediate	Sandy
Desert	24	25	26
Arid	22.5	23.5	24.5
Intermediary	21	22	23
Humid	19.5	20.5	21.5
Wet	18	19	20

3.2. The Modeling of the ground temperature of the City of Biskra

Applying equation (5) for the city of Biskra which is located in the south of Algeria (34 ° 48 ° north of the equator), the soil temperature at a depth of 1m can be determined. Taking the damping factor and the time lag period F and L for arid climates respectively 0.5 and 24.5 from table 1 and 2, and the climatic data of the city of Biskra illustrated in figure 3 (a), the average annual temperature T_{ma} and the amplitude A_o are respectively 10.23°C and 11.48°C. Knowing that:

$$T_{ma} = (T_{max} + T_{min})/2 \quad \text{and}$$
$$A_o = (T_{max} - T_{min})/2$$

T_{max} and T_{min}: the maximum and minimum temperature of the hottest and the coolest month of the year.

4. Results and discussion

From equation 5, the temperature of the ground at a depth of 1m during July (the hottest month in Biskra) is equal to 29.13°C. This level of rather high temperature of the ground does not make it possible for the ground to bring back the inlet air to levels which enable it to be used for convective cooling. According to the studies developed by labs [5], Hayeem [7], and Kusuda [9], the cooling of the surface can be accomplished either by cooling the soil surface, and therefore the cooling of the mass of land that is below or by direct cooling of the soil mass by increasing its relative cooling rate in winter compared to its rate of temperature rise in summer. By a specific treatment of the soil's surface the cooling of the soil in summer allows shading from direct sunlight, increase heat loss by evaporation from the surface and reduce convective heat gains from the ambient hot air.

Protecting the surface from direct solar radiation can be performed by tree canopy, thereby promoting the evaporation of a considerable amount of water from the soil surface and plant leaves. Irrigation of the soil surface and its partial coverage by a layer of straw or wood or gravels also reduces heat gain by convection and increase heat losses by evaporation. When the soil is irrigated air saturated at 60-70% wet ambient temperatures are taken into account in the modelling procedure. Thus, taking the annual temperatures of an air saturated at 70%, the surface temperatures of the treated soil during the hottest and the coolest months are respectively (T_{max}= 24.5 °C and T_{min}= 10.50 °C). An example of the establishment of the wet bulb temperature for the maximum temperature of July is given in Fig. 2. The average annual temperature T_{ma}, and the annual range A_o are respectively 17.50 °C and 7.0 °C. Hence, the simulated temperature of the treated soil at a depth of 1m during the month of July is 21.12 °C.

The annual change in the soil temperature at a depth of 1m in the region of Biskra is illustrated in Fig. 3. The soil temperature at a given depth is estimated on the basis of weather data, which are used in a limit state indicating the energy balance at the soil's surface [10]. The temperature variation at (0.60, 1.00 and 1.40m) depth of an irrigated soil, ambient air saturated at (60%) in the area of Biskra is illustrated in Fig. 4.

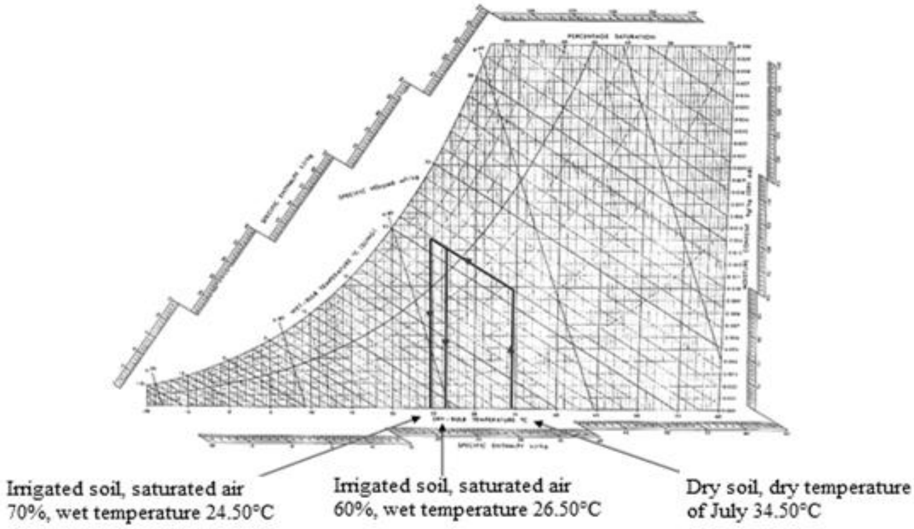

Fig.2. Establishment of the maximum wet temperature of July, ground irrigated at 60% and 70%.

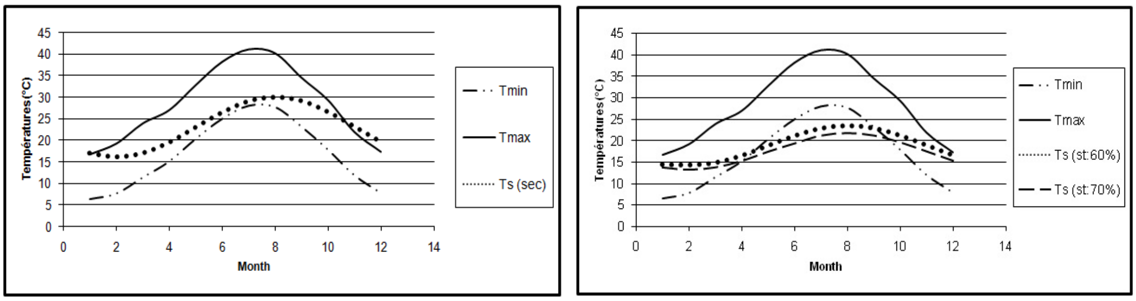

Fig. 3. (a) Variation of a dry ground temperature at a depth of 1m; (b) Variation of an irrigated ground temperature at a depth of 1m, ambient air saturated at (60% - 70%) in the area of Biskra (34° 48° north of the equator).

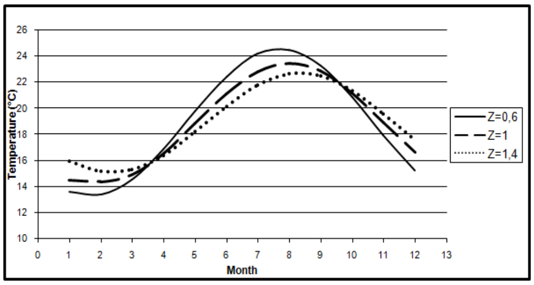

Fig. 4. Variation of an irrigated ground temperature at (0.60, 1.00 and 1.40m) depth in the area of Biskra, ambient air saturated at (60%).

5. Conclusion

The simulated model presented here provides a reasonable method of evaluating the temperature of an irrigated soil at a given depth. The method is estimated on the basis of weather data. The results of this study indicate that if irrigation is applied to the soil's surface in summer the ground offers a good source of cooling for buildings in areas of hot climate. The results of the modelling show that if the surface of the ground is irrigated, air saturated at 60-70%, the temperature of the ground decreases according to the depth and the treatment of the surface of the ground. At a depth of 1m below the surface of an irrigated ground (60%), the temperature of the modelled ground of the area of Biskra during the hottest months varies between 21.11°C and 22.86°C when the outside dry air temperature reaches the 40°C. In fact, a specific treatment at the surface of the ground in summer will further reduce the soil temperature. While the heat is dissipated into the ground at that depth, the temperature of the interface between the soil and the layer of gravels may slightly rise. This in turn will raise the vapour pressure of the soil and increase its evaporative cooling, thus limiting the ground temperature rise.

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