A METHODOLOGY TO DETERMINE THE TEMPERATURE DISTRIBUTION ON THE GROUND UNDER A PLASTIC COVER EXPOSED TO THE SOLAR RADIATION

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Abstract. *This paper presents an analytical and experimental methodology to determine the ground temperature under a translucent plastic cover. The experimental methodology consists on the measurement of the temperature on several depths of the ground, of the airflow temperature, of the airflow velocity and of the incident solar radiation. The mathematical model developed allows one to evaluate the temperature on several depths of the ground, since the external environment temperature, the incident solar radiation and the plastic and ground thermal and optical properties are known. A comparison between numerical results and data obtained in an experimental prototype was done in order to check the mathematical model.*

Keywords. *Solar Heating, Thermal Convection, Temperature Measurement*

1. Introduction

Greenhouses, air solar collectors (Duffie e Beckman, 1991), solar chimneys (Schlaich, 1995) and some types of solar dryers (Schirmer et. al., 1989; Muller et. al., 1996; Condorí et. al., 2003) are basically composed by an absorbent surface placed under a translucent cover exposed to the solar radiation (Fig. 1).

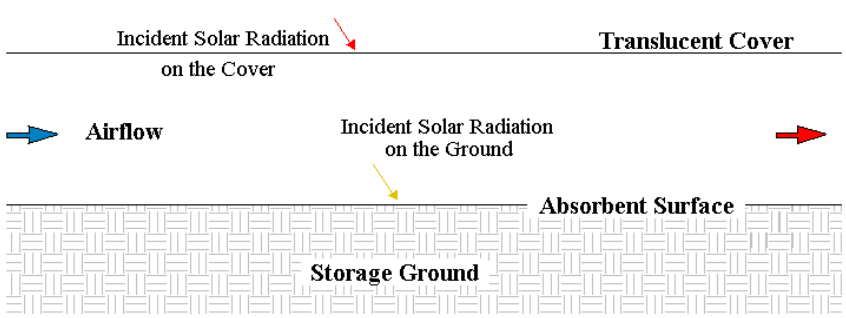

Figure 1 – Schematic drawing of an absorbent surface under a translucent cover

In these devices, part of the incident solar radiation is transmitted by the cover, reaching the absorbent surface, usually the ground. Part of the transmitted radiation is absorbed by the ground and converted in thermal energy, the other part is reflected back to the cover. The solar radiation suffers multiple reflections between the ground and the cover, having its intensity reduced after each reflection. The heated ground transfers heat to the airflow under the cover, through convection, and to the external environment, through radiation. The energy balance is shown in Fig. (2).

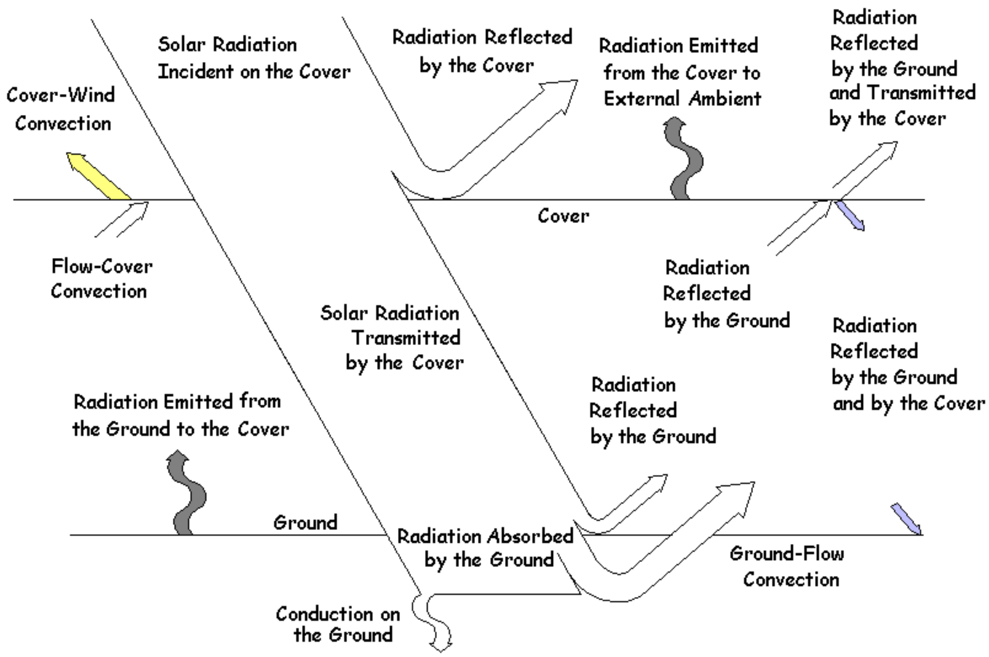

Figure 2 – Energy balance for a ground-translucent cover system

The greenhouse type solar dryer presented by Ekechukwu and Norton (1999) uses the ground under a translucent plastic cover as a surface to absorb solar radiation, in order to dry large amounts of products. Basunia and Abe (2001) present a mixed mode passive solar dryer used to dry grains, with a similar structure to collect radiation. The determination of the absorbent surface temperature is an important factor in the energy balance of thermal equipments that work by this mechanism.

This paper proposes an analytical and experimental methodology to determine the temperature distribution on the ground, regarding to the known incident solar radiation on the absorbent surface. The mathematical results were compared to the results obtained in an experimental assemblage in order to check if the model used represented properly the physical phenomenon studied.

2. Mathematical Modeling

The hypotheses considered in the formulation of the mathematical model were: one-dimensional heat conduction, isotropic and homogeneous material with constant properties, ground as a semi-infinite solid, flat ground surface and the air as a transparent means.

The unidimensional heat diffusion equation, in unsteady state, without internal heat generation, can be calculated by (Incropera and DeWitt, 1992)

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{1}$$

In order to obtain the solution of this problem, two boundary conditions for the $\boldsymbol{x}$ spatial coordinate and one initial condition for time are needed.

The first boundary condition can be obtained through a thermal balance on the ground surface. The liquid heat flux absorbed in the surface, given by the difference between the solar radiation absorbed by the ground ($\boldsymbol{S}$) and the heat flux transferred to the airflow and to the cover ($\boldsymbol{q''}$), is transmitted through conduction to the deeper layers of the ground.

$$q''_{liq} = S - q'' = -k \frac{\partial T}{\partial x}\bigg|_{x=0} \tag{2}$$

The heat flux that leaves the ground is equal to the sum of all the heat flows that leave the system. Part of this heat is transferred by convection to the airflow and the rest of it is transferred through the cover material to the external environment, by convection and by radiation. The radiation energy exchanged between the ground and the external environment is not considered (the cover material does not transmit infrared radiation).

The heat flux transmitted to the hot airflow by convection, q''_{conv}, can be calculated through the air enthalpy variation.

$$q''_{conv} = \frac{mc_p\left(T_{out} - T_{in}\right)}{A} \tag{3}$$

T_{in} and T_{out} represent, respectively, the average temperatures of the flow at the inlet and at the outlet of the system. A represents the area where there is heat exchange between the ground and the flow.

The radiation heat flux exchanged between the cover and the external environment can be modeled by (Incropera and DeWitt, 1992)

$$q''_{rad} = \varepsilon\sigma\left(T_{cob}^4 - T_{amb}^4\right) \tag{4}$$

where T_{cob} represents the temperature of the cover and T_{amb} the temperature of the external environment.

The convection heat flux between the cover and the external environment, q''_{conv2}, can be modeled by (Incropera and DeWitt, 1992)

$$q''_{conv2} = h\left(T_{cob} - T_{amb}\right) \tag{5}$$

Considering the flow over the cover similar to the flow over a flat plate, the convective coefficient can be calculated by

$$h = \left(0{,}037\,Re_L^{4/5} - 871\right)Pr^{1/3}\frac{k}{L} \tag{6}$$

Re_L represents the global dimensionless Reynolds number over a flat surface, Pr, the Prandtl number, k, the air thermal conductivity and L represents the characteristic length of the surface.

The second boundary condition can be obtained considering the ground as a semi-infinite solid. Therefore, the temperature in a quite far position is equal to the average external environment temperature.

$$\lim_{x \to \infty} T(x,t) = T_o \tag{7}$$

The initial condition is obtained assuming that, at the beginning of the simulation, the ground is at a constant temperature and at the same average temperature of the external environment.

$$T(x,0) = T_o \tag{8}$$

The exact response to the problem, with the previous boundary and initial conditions, is given by (Özisik, 1993)

$$T(x,t) = T_i + \frac{2}{\sqrt{\pi}}\frac{\alpha}{k}\int_{t'=0}^{t}\frac{q''_{liq}(t')}{\sqrt{4\alpha(t-t')}}e^{-\frac{x^2}{4\alpha(t-t')}}dt' \tag{9}$$

t is the real time and t', the integrate variable.

3. Experimental Methodology

In order to evaluate the mathematical model, a prototype was constructed at the Universidade Federal de Minas Gerais. The prototype constructed consist of an absorbent surface (ground with a thin concrete layer, painted in black) covered by a translucent plastic thermo-diffuser film, 150 μm-thick, placed 50 cm far from the ground.

The instruments used in the experiments were five K thermocouples, maximum uncertainty of 2ºC, an anemometer with maximum uncertainty of 8%, and six Eppley Black and White pyranometers, which have a measurement uncertainty of 5%. The mentioned uncertainties were obtained considering a confidence level of 95%, referring to the sensor-system data acquisition assemblage.

The anemometer and one of the thermocouples were placed 25 cm above the ground surface, monitoring, respectively, the airflow velocity and temperature. Another thermocouple was maintained in the external environment, measuring its temperature. The others were used to assess the temperature distribution profile from the ground surface (0 cm) to increasing distances in the soil column, at depths of 20 cm and 45 cm.

The pyranometers were placed in a way to allow the determination of the optical properties of the ground and in the cover materials. They were arranged as shown in Fig. (3).

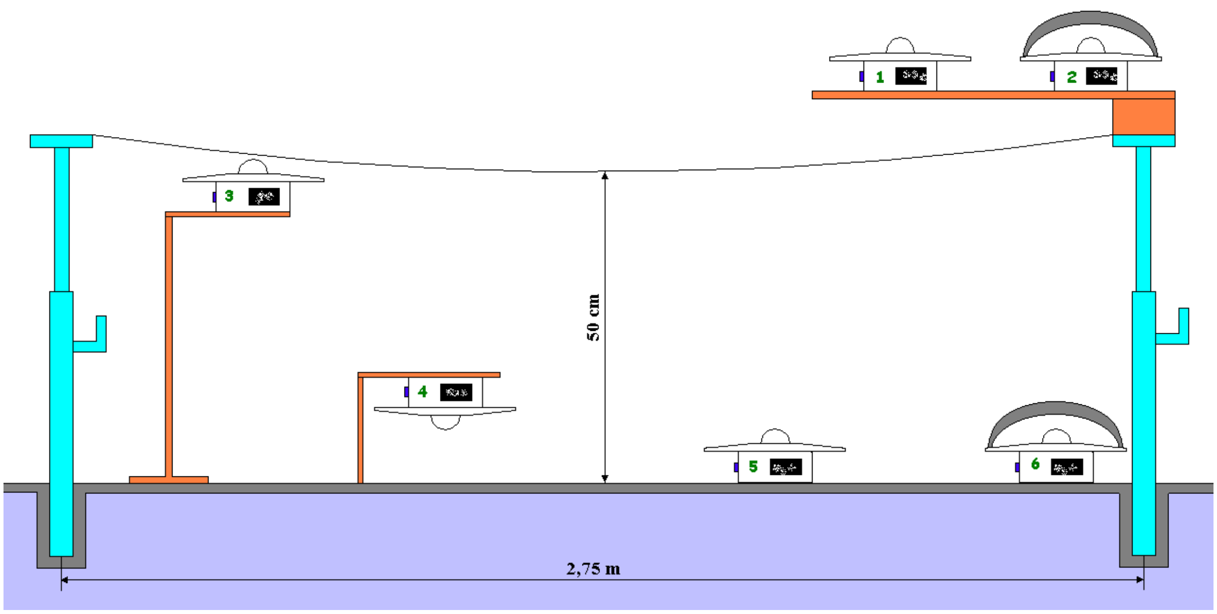

Figure 3 – Arrangement of the pyranometers

The pyranometer identified by the number **1** in Fig. (3) detects all the incident solar radiation on the cover. The pyranometer identified by **3** receives the solar radiation that passed through the cover. Pyranometer **4** detects the radiation reflected by the ground, and pyranometer **5** receives the global radiation (sum of the direct and diffuse portions) incident on the absorbent surface. The pyranometers indicated by the numbers **2** and **6** are covered by shading rings, which block the direct portion of the solar radiation. Therefore, they receive the diffuse radiation incident on the cover (pyranometer **2**) and on the surface (pyranometer **6**).

The radiation absorbed by the ground can be calculated by the difference between the values read in the pyranometers indicated by the numbers **4** and **5**; this means that the radiation absorbed is the difference between the incident radiation and the radiation reflected by the absorbent surface. If the radiation read in a pyranometer ***i*** is indicated by G_i, the radiation absorbed by the surface is given by

$$S = G_5 - G_4 \tag{10}$$

The optical properties were calculated comparing the values read on the other pyranometers. Armoring laterally pyranometer **3** against reflected and diffuse radiation, the optical transmittance of the cover can be calculated as the ratio of readings from pyranometers **3** and **1**.

$$\tau_{cob} = \frac{G_3}{G_1} \tag{11}$$

The transmittance is the property of the cover in which there is greater interest, since it determines the portion of the incident radiation that will pass through the cover. The other properties are not so important; therefore they will not be calculated in this paper. If there is interest in knowing them, other pyranometers must be arranged in a way to receive the portions of radiation reflected and absorbed by the cover.

The absorptance of the absorbent surface is calculated as the absorbed radiation to the incident radiation over the surface ratio.

$$\alpha_s = \frac{G_5 - G_4}{G_5} \tag{12}$$

The reflectance of the surface is given by the reflected radiation to the incident radiation on the surface ratio.

$$\rho_s = \frac{G_4}{G_5} \tag{13}$$

4. Results

The simulation of the mathematical model was performed through the integration of Eq. (9), using the trapezium law. The ground was considered composed only by soil, not considering the superficial concrete layer, as it is very thin. The values for the thermal properties of the ground (thermal diffusivity and thermal conductivity) used were obtained in Incropera and DeWitt (1992).

The convection and radiation thermal losses by the ground surface to the flow were calculated using the measured values of velocity and temperature of the flow.

The experiments were performed on the 5th and 6th of February, 2003. The sampling interval used was 60 s. The flow velocity values varied from 0,5 m/s to 2,5 m/s, used to feed the simulation program.

Figures (4) and (5) present the measured values of the incident global solar radiation over the plastic cover and the calculated values of the global solar radiation, without atmospheric attenuation, for the same locality. Values of the diffuse incident solar radiation over the cover measured on the 6th of February are presented. The daily average clearness index Kt is defined as the ratio of the daily incident solar energy on a horizontal surface to the daily extraterrestrial radiation (maximum solar energy that could achieve this surface). In the data collected in the first day of experiments, it can be observed that the incident energy corresponds to 70% of the available extraterrestrial energy (Kt = 0,70). For the second day, the clearness index encountered was superior to the one of the day before (Kt = 0,83).

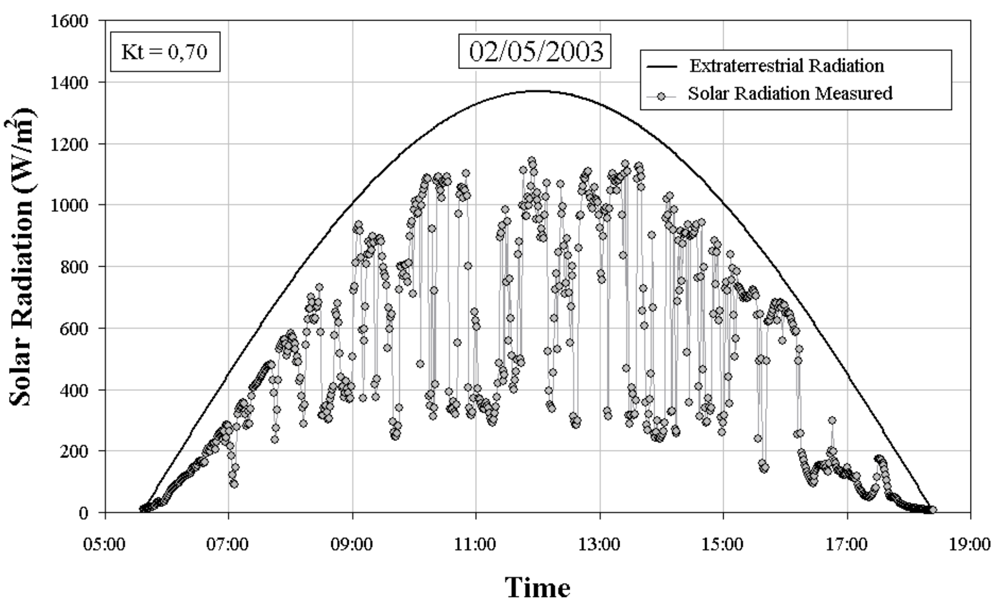

Figure 4 – The solar radiation distribution over the cover on 05/02/03

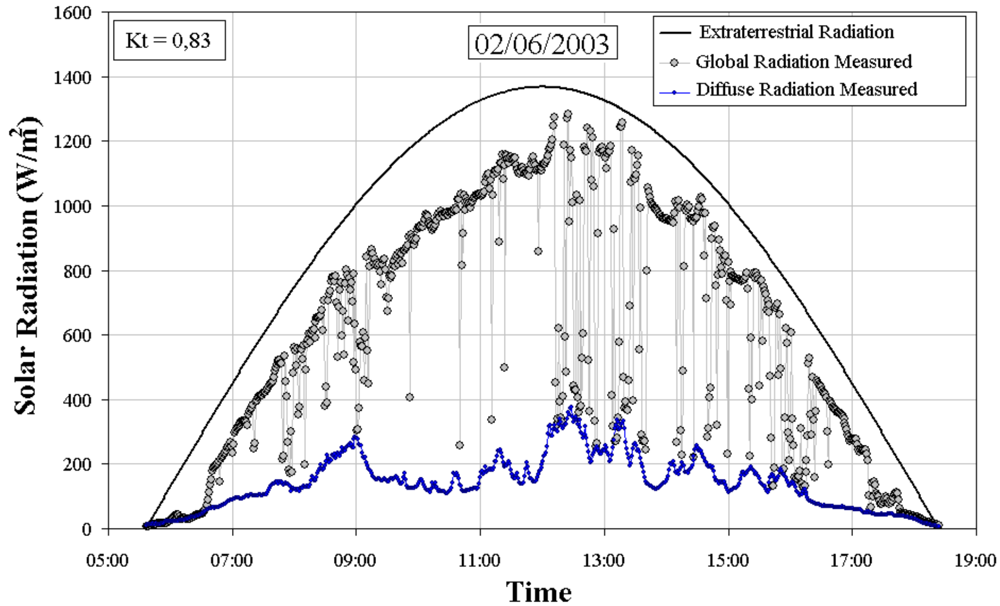

Figure 5 – The solar radiation distribution over the cover on 06/02/03

The optical properties of the ground and of the cover are presented in Fig. (6). They were calculated through Eqs. (11) and (13) using the solar radiation values measured on February 6th. The transmittance of the cover material varied from 50% to 80%; the higher value occurred when the sun was in zenith (noon). Figure (7) presents the variation of the solar radiation incidence angle (angle between the beam radiation on a surface and the normal to that surface). It can be noticed that the transmittance depends on the solar radiation incidence angle, presenting lower values when the incidence angle gets wider. The absorptance of the concrete painted in black, used as an absorbent surface, presented the approximate value of 90%. Consequently, the reflectance of the ground material was close to 10%.

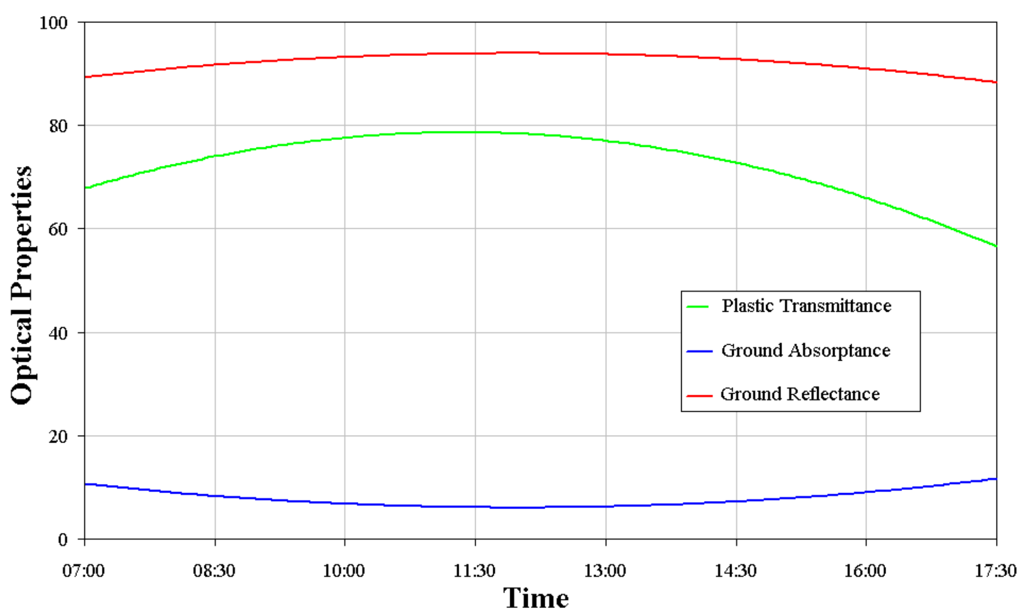

Figure 6 – Ground and cover optical properties

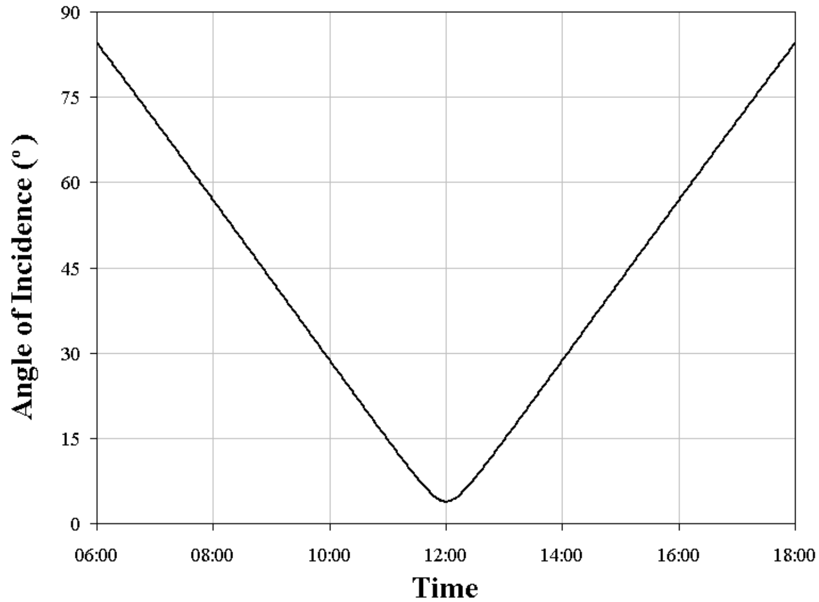

Figure 7 – Incidence angle of solar radiation

Figure (8) presents the behaviour of the ratio of the diffuse radiation to the incident global radiation over the cover and of the ratio of the diffuse radiation to the incident global radiation over the ground (under the cover). The high values encountered for the fraction over the cover can be explained by the presence of clouds in the sky, strongly attenuating the incident global solar radiation. In periods when the sky is not very cloudy, this ratio is lower then 35%. Under the cover, the ratio of the diffuse to the global radiation varied from about 60% to 98%, showing that the plastic film used in the cover has thermo-diffuser features. This behaviour indicates that the plastic spreads a great part of the incident solar radiation over the cover.

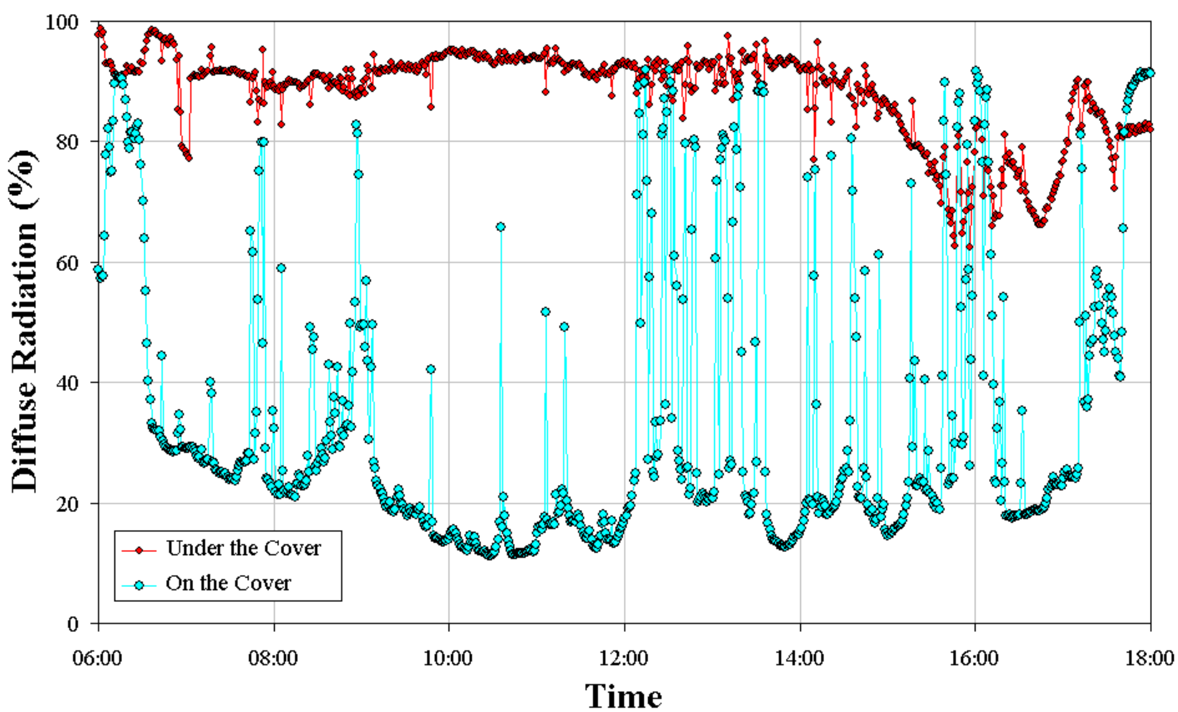

Figure 8 – Behaviour of the plastic film

The temperatures on the surface and on 20 cm and 45 cm ground depths can be observed in Fig. (9). The full lines represent the numerical values and the dots represent the experimental values, for the same depths. The temperature values encountered on the second day are higher than those encountered on the first, since the solar radiation indexes were higher on the 6th of February.

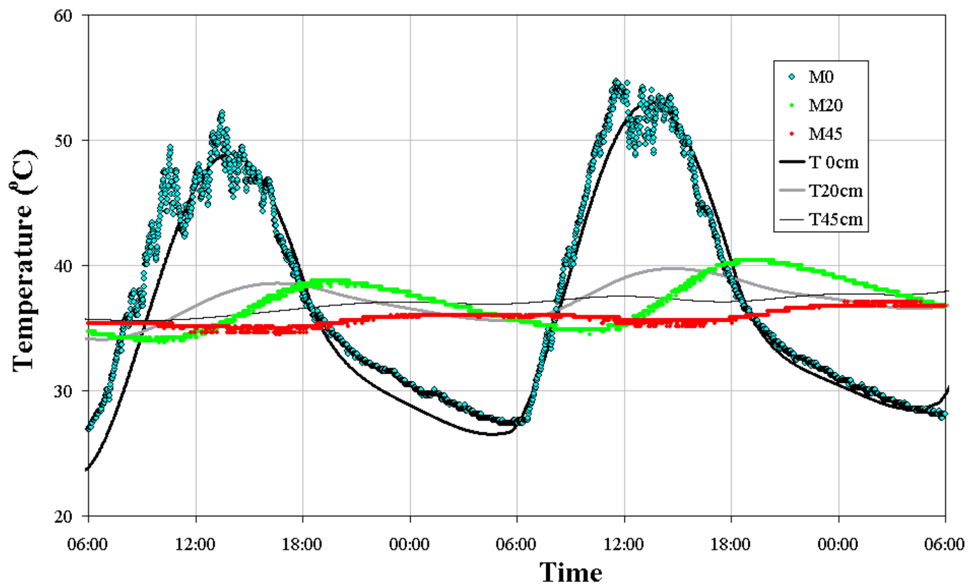

Figure 9 – Temperature distribution on the ground

Figure (10) presents the relative deviations among the numerical and the experimental temperature values (in °Celsius), for the depths of 0 cm, 20 cm and 45 cm. The greater deviations were of 16%, determined for the ground surface.

The adopted model was capable of describing qualitatively the temperature variation throughout the ground depth. The high deviations encountered are due to the simplifications in the mathematical model. Firstly, the influence of the concrete surface was not considered, assuming the ground as a homogeneous and isotropic material. The values of the thermo-physical properties adopted for the ground (absolute density, specific heat and thermal conductivity) were estimated. Moreover, the temperature distribution was considered one-dimensional.

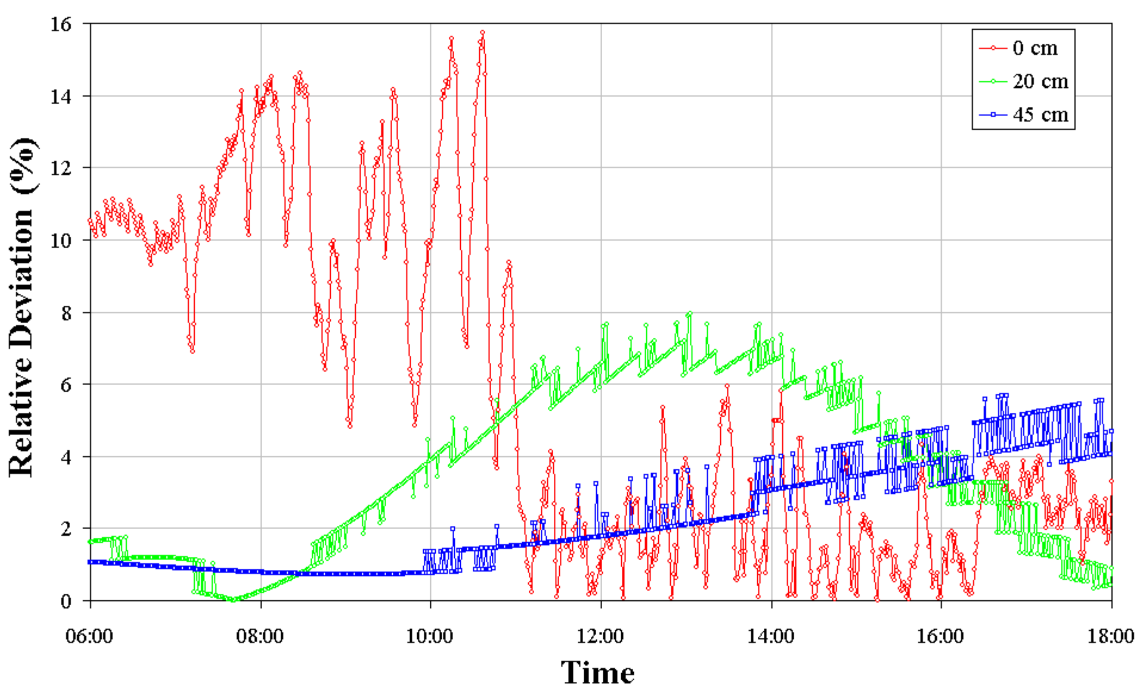

Figure 10 – Relative deviations among the temperatures

5. Conclusions

A mathematical model was developed to determine the temperature distribution throughout the ground depth, under a translucent plastic cover exposed to the solar radiation. The actual thermal behaviour of the ground was evaluated through measurements of velocity, temperature and solar radiation in an experimental prototype. Although it presents high deviations compared to the experimentally obtained data, the adopted model gives simple and fast response to the problem, capable of describing qualitatively the thermal behavior of the ground and of presenting an appraisal of the expectable temperature distribution.

An evaluation of the optical properties of the materials used in the physical model for the ground and for the cover was performed. The values of the cover transmittance indicate that the material used allows a great portion of the incident solar radiation to pass through the cover. Besides, the ground absorptance was of about 90%, indicating that the surface material is capable of absorbing great part of the incident radiation.

The developed methodology allows the determination of the instantaneous temperature in an absorbent surface under a translucent cover, knowing its optical and thermal properties and the incident solar radiation on the surface. The determination of such temperature is the solution to one of the main problems in the project of solar devices such as solar dryers, solar chimneys and greenhouses.

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