A Dynamic Model for the Determination of Thermal Boundary Conditions in the Ground of a Greenhouse

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Abstract

This paper deals with the description of a semi analytical model built to predict the temperature and heat flux conditions at the ground level of a greenhouse. The objective of this work is to provide these as boundary conditions for use in a CFD model for the accurate determination of the climatic conditions in a greenhouse.

The main source of energy contained in the ground comes from the solar radiation which may fluctuate considerably depending on the daytime, place, season, clearness of the sky and albedo of the surface. In the ground, the heat transfer depends on its physical properties, compactness and moisture. The ground is a porous environment which contains air and water at variable quantities in the interstices, which makes heat transfer analysis by conduction much more complicated than in usual homogeneous solid bodies. The temperature profile resulting from the heat balance at the surface depends on the thermal diffusivity of the soil. Many works use the average value of this physical characteristic by regrouping parameters for estimating the temperature profile.

In this study, we are concerned by the estimation of the ground response for some known transient ambient environment conditions (solar radiation, temperature, hygrometry and wind speed). Using a semi-analytical method, the ground temperature profile is determined from weather parameters and the ground characteristics. This method helps in evaluating the heat flux exchanged between the ground surface and the ambient air; this procedure differs from other procedures which consider a steady state average value of the heat flow.

INTRODUCTION

The rapid progress in numerical modelling of the climate in greenhouses provides hope that it will soon be possible to take into account the dynamic, rather than the static, behaviour of the greenhouse as has been the case until now (Montero & *al*, 2004; Haxaire, 1999; Bartzanas & *al*, 2002; Chemel, 2001). For this, it is necessary to take into account the inertia of the ground and to integrate it into the models, of particular interest are the lower boundary conditions of the domain concerned by the models. It is not easy to make a complete heat balance in the ground because of the complexity of the phenomena involved.

By knowing the temperatures distribution laws in the ground, it is possible to consider heat stored in a layer of given thickness. This temperatures distribution is the result of the radiative exchange together with the heat and mass transfer between the ground and its environment and the heat and mass transfers between various layers of the ground.

During a period of 24 hours, the surface temperature profile is the response to the diurnal radiation. The inertia intervenes in the ground, where ground parameters (thermal conductivity) are determinant in heat exchange (Crausse & *al*, 1981).

In the case of a one year period (Guyot, 1992; Kimball, 1982), the signal can be decomposed into a convergent series of sinusoidal functions (cosine and sine). Knowing this mathematical signal at the surface makes it possible to express the vertical temperature profile in the ground, by means of an exponential term. Consequently, the temperature signal tends towards a constant value below a depth of 1m.

The transfer of heat, during a day, affects the ground only in a thin layer of a few tens of centimetres. The daily storage of heat in the ground (thermal inertia) concerns the first layer of the ground which does not exceed 0.6m.

On the other hand, phenomena observed for a one year period are quite different. Indeed, considering the day average values makes it possible to represent the signal on the surface during this period. This periodic signal can also be decomposed into series of sinusoidal signals. A similar exponential term affects the vertical temperature distribution in the ground and for a depth of greater than 10m, the signal remains almost constant. Consequently, the heat transfer occurs only in the superficial layer which can restore, to the ambient air, part of the stored energy.

METHODS

We perform in this study, a heat balance in a ground considered as being an isotropic and semi infinite, homogeneous medium, receiving a signal at its surface. The transient heat transfer equation, Fourier's equation, for a thickness element dz and with a sufficiently large surface in order to neglect the edge effects (Fig. 1), is:

$$\frac{\partial\theta}{\partial t} = \alpha\frac{\partial^2\theta}{\partial z^2} \qquad (1)$$

With $\theta=\theta$ (z,t) and $\alpha=\frac{\lambda}{\rho Cp}$ the diffusivity of the ground which remains appreciably constant at a depth of 0.6m.

Taking into account the observations of experimental measurements, the temperature distribution at a depth z in the ground is:

$$\theta(z,t) = \theta o + A_S e^{\frac{-z}{z_d}} \sin\left[w(t-t_0) - \frac{z}{z_d}\right] \qquad (2)$$

Where:

θ_0: the temperature of the deep ground towards which $\theta(z,t)$ tends when z tends towards infinity.

A_s: the amplitude of the signal.

$w = \frac{2\pi}{T}$: The frequency of the signal (3)

T: The period (equal to 24 for a period of 24 hours (Fig. 2) and equal to 365 for the variation of the daily average temperatures during a year (Fig. 3),

$$z_d = \sqrt{\frac{2\alpha}{w}} \text{ : damping parameter} \qquad (4)$$

t_0: Moment of the day for which the temperature on the surface ground becomes equal to θ_0.

Generally, equation (1) for the conduction of heat admits a solution of the Fourier series type that can be written in the following form:

$$\theta(z,t) = \theta_0 + \sum_{1}^{k=\infty} \left\{ a_k \cos\left[k\left(w_1 t - \frac{z}{z_d} \right) \right] + b_k \sin\left[k\left(w_1 t - \frac{z}{z_d} \right) \right] \right\} e^{\frac{-z}{z_d}} \qquad (5)$$

It appears (Guyot, 1992) that the variation in temperature follows a periodic function of time. For a periodic signal, with a 24 hour period, one observes a time variation of the temperature whose amplitude deceases quickly with depth (Makhlouf, 1988) (Fig. 2). On the other hand for a year period, the damping of the signal is less and the temperature variation penetrates to a greater depth (5 to 6m depending on the thermophysical parameters of the ground) (see Fig. 3).

The ground temperature distribution during a day

In order to characterize the temperature distribution in the ground over a 24 hour period, we exploit the experimental distribution at the surface of the ground, together with data at depths of - 0.1, - 0.2 and -0.3m (Antibes climate, June 21st 1985 (Makhlouf, 1988). The complexity of the analytical solution of equation (1) requires the consideration of numerical solution techniques. The Computational Fluid Dynamics code, Fluent® makes this possible because it can also solve conductive transfers. With this idea in mind, we have introduced into Fluent® the characteristic data of the ground (specific heat: 1464.75 KJ m^{-3} K^{-1}, thermal diffusivity: $3.1\ 10^{-7}$ m^2 s^{-1}) for a 0.3m depth with its associated boundary conditions: imposed measured temperatures at the surface (Fig. 4) and at -0.3m.

The computation results show that there was good agreement between the measured values and those calculated using Fluent® for depths of -0.1 m and -0.2 m (Figs 5 and 6).

This study has shown that a numerical simulation successfully provides transient ground temperature profiles with only the evolution of surface temperature as the boundary condition.

Ground temperature in Avignon (South of France)

In the area of Avignon, the prevailing wind is the Mistral wind from the North-West and North, that blows in the North of the basin of the Western Mediterranean. With these wind conditions the variation between the temperature on the surface of the ground and the air temperature 10 m above the ground is lower than 0,1 °C (Guyot, 1992; Bartzanas & *al*, 2002). The weather data exploited here contain statements of temperatures (over a 20 year period) at a height of 2m (Fig. 7), we write then:

$$\theta(0,t) = \theta_{air} \qquad (6)$$

Taking expression (6) into account, the daily average temperature for the n^{th} day of the year (n varying from 1 to 366) is:

$$\overline{\theta(0,t)} = \overline{\theta_{air}} \qquad (7)$$

The daily average temperature of the ground surface $\bar{\theta}(0,n)$ can be broken up as follows:

$$\bar{\theta}(0,n) = \theta_0 + \sum_{k=1}^{5}\left\{C_k \cos[k(w_2.n)] + D_k \sin[k(w_2.n)]\right\} \qquad (8)$$

Where: $\theta_0 = \frac{1}{T}\int_{n=1}^{366}\overline{\theta_{air}}dn$

The parameters of the Fourier's function are then given by:

$$C_k = \frac{2}{T}\int_{1}^{366}\overline{\theta_{air}}\cos(kw_2 n)dn \qquad (9)$$

$$D_k = \frac{2}{T}\int_{1}^{366}\overline{\theta_{air}}\sin(kw_2 n)dn \qquad (10)$$

$$w_2 = \frac{2\pi}{366} \qquad (11)$$

From Fig. 7 it is clear that five terms only are enough to represent accurately the change of ground surface temperature over a year period.

Therefore we say that the annual distribution of the ground temperature field for the area of Avignon is in the form:

$$\bar{\theta}(z,n) = \theta_0 + \sum_{k=1}^{5}\left\{C_k \cos[k(w_2.n - \frac{z}{z_d})] + D_k \sin[k(w_2.n - \frac{z}{z_d})]\right\}e^{\frac{-z}{z_d}} \qquad (12)$$

With:

C_1= -9,9221 ; C_2=0,1925 ; C_3= -0,1073 ; C_4 = -0,0954 ; C_5 = 0,1604,

D_1 = -3,9558 ; D_2=1,6471 ; D_3= -0,4646 ; D_4= -0,1156 ; D_5= -0,1421.

n = number of the day of the year.

Temperature distribution in the ground in Avignon

In the light of the results, we can discern two zones, the first zone relates to depths of less than 0.6 m in which the temperature profile varies over a period of 24 hours, and the second zone in which the signal is not affected for this period. For a period of one year, the disturbance can reach a depth of up to 6 m depending on the properties of the ground.

Boundary conditions

On the surface of the ground we impose the air temperature profile for March 21st (Fig. 8) which constitutes the average value over 20 years, below a depth of 0.6 m we impose the temperature profile given by equation (12) (constant for a period of 24 hours but variable over a period of 366 days).

RESULTS AND DISCUSSION

Simulation, with the CFD Fluent® code, gives the change of the temperature of the ground for March 21st, at various hours of the day, illustrated by the curves in Fig. 9.

In Fig. 10 we observe a considerable variation of temperature distribution in the thin surface layer for the various hours of the day. Below 0.6 m the various curves tend towards the same value of temperature. Below 7 m the temperature tends towards 13 °C, the average value of the ambient air during the year.

CONCLUSION

This study makes it possible to supplement the description of numerical models of the greenhouse climate by taking into account boundary conditions that are much more realistic than those which we used until now; in particular at the level of the ground.

Measurements of the evolution of air temperature over a period of one year allowed us theoretically to approach this periodic signal with Fourier series. This signal has been taken into account for the determination of the profile of temperature on the ground surface. The model established by Makhlouf (1988) for the distribution of temperature in the ground for the climate of the south of France (Antibes, Alpes Maritimes) and validated by experimental measurements authorizes us to use these values as boundary conditions in numerical simulations performed with Fluent® CFD code.

It was also shown that the distribution of temperature in the surface layer of the ground (0 to 0.6 m) for March 21st in Avignon, could be simulated in a very satisfactory way by the Fluent® CFD code, which is used for modelling greenhouses.

To simulate the thermal response of the ground during a day, two boundary conditions were introduced. On the surface, the profile of air temperature was imposed and with the depth below 0.6 m, the law of distribution (12) which represents the in-depth variation of the daily average temperatures.

This study enables us to define the temperature field in the ground for various hours of the day during the whole year on the surface and underground. These temperature profiles constitute a boundary condition for complete models of greenhouse climate including the ground and enable the conduction heat flux to be evaluated on the ground surface for diurnal and night periods.

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Notation

α: thermal diffusivity. Cp: heat-storage capacity λ: thermal conductivity. ω: frequency of the periodic signal ρ: density	T: period θ: temperature. θ_0: temperature of the deep ground. $\bar{\theta}$: average day temperature

<u>Figures</u>

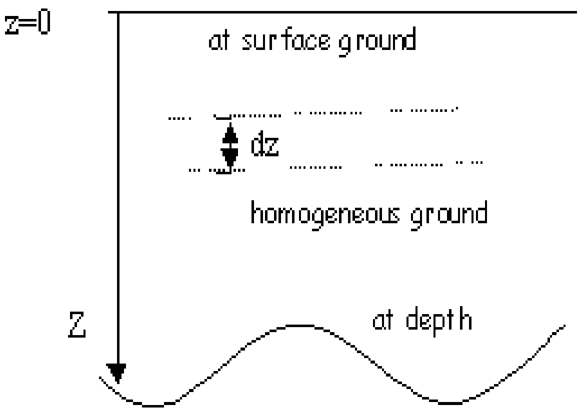

Fig.1: Schematization of the element of volume in the ground

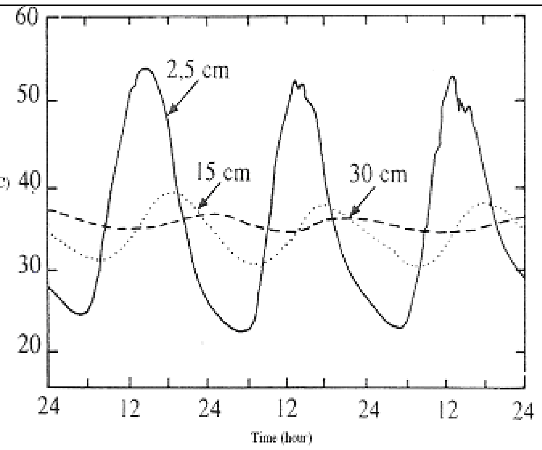

Fig.2: Temperature evolution during 24 hours

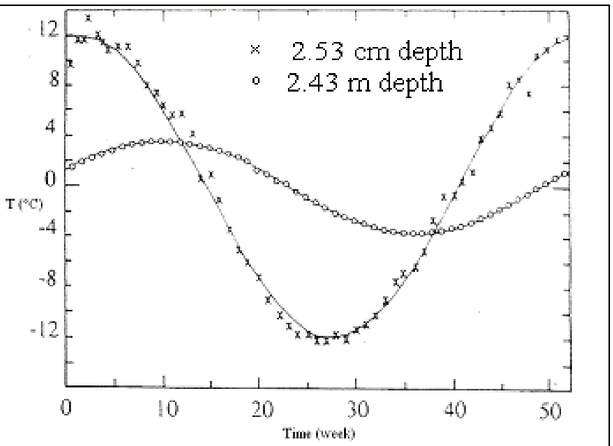

Fig.3: Temperature evolution during 365 days

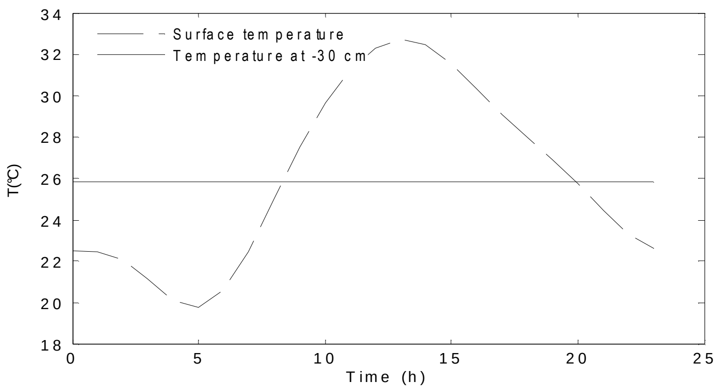

Fig.4: Profile of the measured temperatures, during June 21, 1985, on the surface of the ground and at a 0.3 m depth (Makhlouf, 1988) (Antibes).

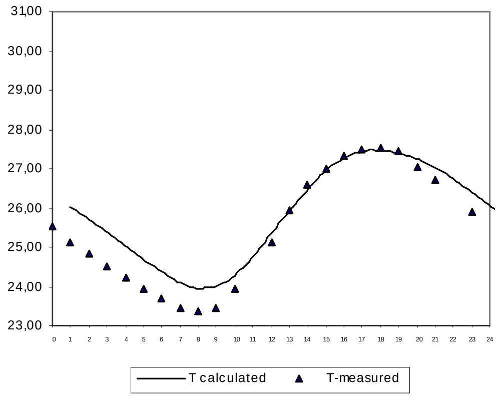

Fig.5: Temperature distribution 0.1m below the ground surface

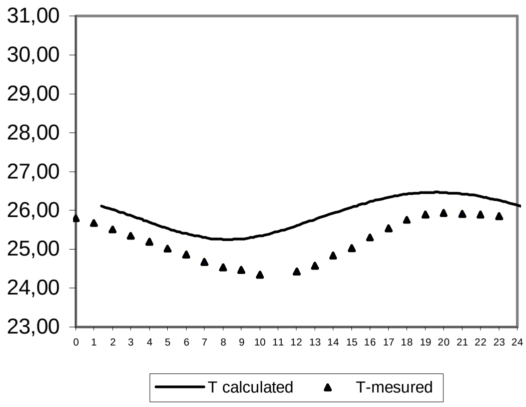

Fig.6: Temperature distribution 0.2m below the ground surface

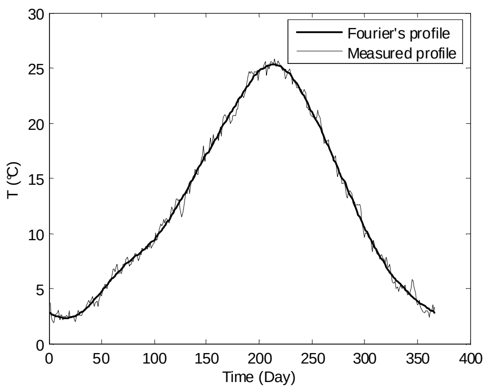

Fig.7: Measured and simulated temperature profile of the air

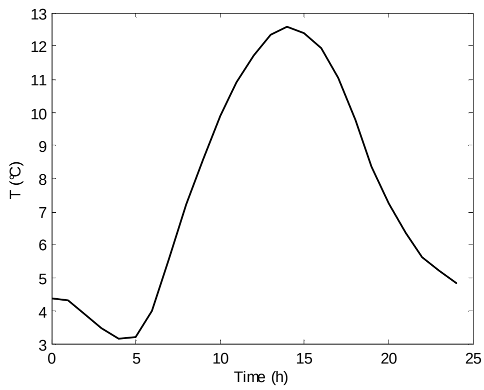

Fig.8: The climate air temperature profile measured for the March 21st day in Avignon region

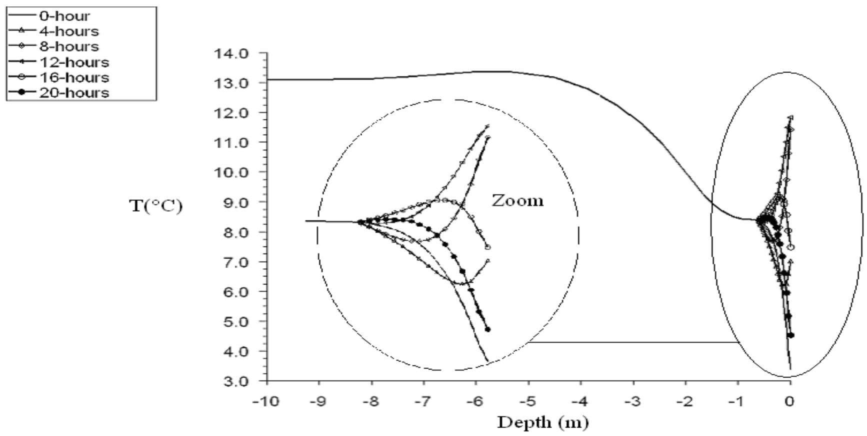

Fig.9: Temperature profile of the ground to a depth of 10 m

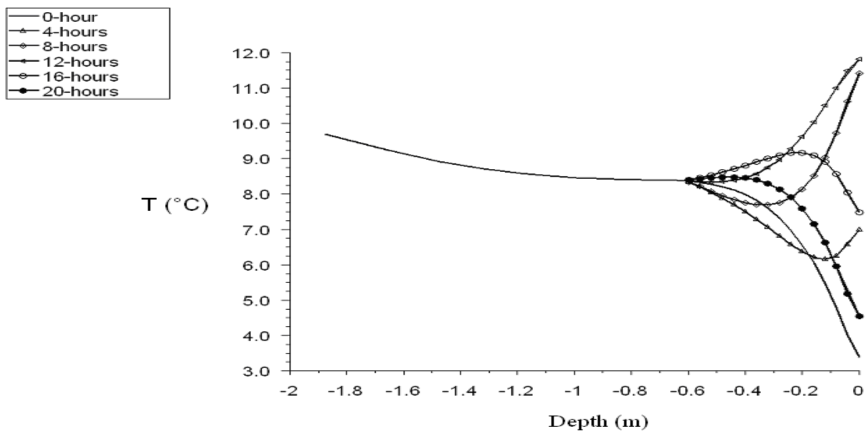

Fig.10: Enlargement of the ground temperature profile between 0 and 2 m