International Journal of Agricultural Research

ISSN 1816-4897

Academic
Journals Inc.

www.academicjournals.com

International Journal of Agricultural Research 6 (6): 458-469, 2011
ISSN 1816-4897 / DOI: 10.3923/ijar.2011.458.469

Numerical Analysis of the Influence of Soil-Air Convective Heat Transfer Coefficient on the Global Indoor Climate Model of a Closed Plastic Tunnel Greenhouse

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ABSTRACT

Crop growth in greenhouses is strongly influenced by the local inside climate. In the present study, a model for predicting the thermal and water behaviour inside an unheated closed plastic tunnel greenhouse is presented. The energy balance method is applied to each element of the shelter: cover, indoor air and soil surface. Radiative transfers are included by calculating view factors. This model is connected to another model for the subsoil. The corresponding modules were integrated in the TRNSYS (Transient Simulation system) environment. TRNSYS includes weather data and calculates the solar radiation distribution, sky temperature and psychrometric properties. The simulations predict three main parameters under transient conditions: the indoor air temperature, the soil temperature and the indoor humidity. The present study also focuses on the cover temperature in response to the inside and outside conditions. Results provided by the model were validated with fair agreement against experimentations conducted for an unheated closed plastic tunnel greenhouse located in Angers (47.43N, 0.55°E). Based upon the results of the simulations and the experimentation, it is shown that the convective heat transfer between the soil surface and the indoor air affects significantly the indoor climate. Moreover, the use of correlations of this coefficient depends on the direction of heat flow; a specific correlation is applied with upward heat flow and another one with undergoing downward heat flow.

Key words: Greenhouses, TRNSYS, convection, transient simulation, indoor temperature, indoor humidity

INTRODUCTION

In recent years, the cost of fossil energy considerably increased, making the crop production inside greenhouses more expensive. For that reason, there is an urgent need to implement better practices in energy management in order to reduce energy costs (Heidari and Omid, 2011).

Modeling tools can help to predict the climate evolution inside a greenhouse and adapt a strategy to reduce the energy consumption. The design of a greenhouse depends upon the latitude of the place and the requirement of crop (From a physical point of view, a greenhouse may be considered as a solar energy tank (Kumar *et al.*, 2006) and the most of solar radiation incident on a greenhouse is absorbed by components (Abdel-Ghany and Al-Helal, 2010). A large amount of this energy reaches the greenhouse during daytime and warms the inside air but most of the energy is not stored and is evacuated through the openings (Rico-Garcia *et al.*, 2008). Artificial heating is therefore, sometimes required (Kumari *et al.*, 2006), particularly at night time in winter. For that reason, it becomes urgent to optimize the use of unheated greenhouses and better exploit heat storage inside the ground.

Numerous numerical studies on greenhouse indoor climate have been conducted to predict the greenhouse thermal environment. Some of them are based on a global approach which consists in writing the energy balance of the different elements of the greenhouse as well as the water vapour balance inside the greenhouse (Fitz-Rodriguez *et al.*, 2010; Shukla *et al.*, 2006). The developed thermal-simulation models mainly use measured transmittivity of the cover (Kittas *et al.*, 1999) or constant values (Singh *et al.*, 2006). Moreover, they usually consider all surfaces of the cover to have the same temperature and assume that internal thermal radiation exchanges only occur between the cover and the ground and exchanges with the outside ground are therefore, neglected. The weakness of these studies is that they do not consider the different components of the greenhouse cover although they to not behave in the same way. Recently however, Kolokotsa *et al.* (2010) took account of the thermal radiation between cover surfaces and introduced view factors as input data and the greenhouse shape is considered as paralleled enclosure.

A greenhouse simulation model (GGDM: Gembloux Greenhouse Dynamic Model) was developed by Pieters and Deltour (1999) and used by Wang and Boulard (2000) to describe the evolution of the climatic parameters inside a greenhouse. The model GGDM is implemented in the TRNSYS environment and requires as input data the global and the diffuse radiation. Nevertheless, only the global radiation is measured by the most meteorological stations.

The objectives of the present study were to develop two new modules in the TRNSYS environment, one to simulate the greenhouse behavior and the second one to simulate the subsoil transfers. The inputs of the greenhouse model are provided by the other standard modules and by the subsoil module. To validate the greenhouse module, experimental data were collected and a comparison of the impact of the soil-to-air heat convection by using three different correlations from the literature. The validity of these correlations over the time was also checked.

MATERIALS AND METHODS

TRNSYS is a transient simulation program with a modular structure. This modular structure makes it easy for users to add new components to the standard package. In the present study two new modules have been implemented in order to cope with the specificities of the greenhouse system. The first one deals with the greenhouse itself: cover, indoor air and soil surface. The model provides information at each time step on the thermal behavior by calculating the temperature of each component of the greenhouse. The second one provides temperature profile in the subsoil. The aim of these differentiated modules is to separate the low capacity component of the system (i.e., the greenhouse) from the high capacity component of the system i.e., subsoil. The distinction of different portions of cover following the slope and azimuth solar angle makes it possible to take account of both the incident solar radiation and the wind direction in the convective coefficient determination.

A greenhouse is a production system made of thee main elements: the transparent cover, the indoor air and the soil surface. The cover acts as an interface between the microclimate and the outside climatic conditions and the soil surface as an interface between the microclimate and the subsoil. The outside climate, the greenhouse (cover, indoor air and soil surface) and the subsoil may then be formalized by using a modular approach. In this prospect, two new modules for the

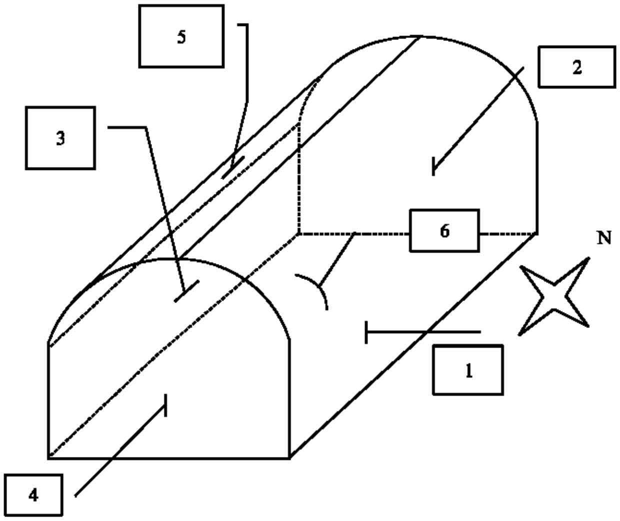

Fig. 1: Greenhouse orientation and nomenclature of the different elements of the greenhouse

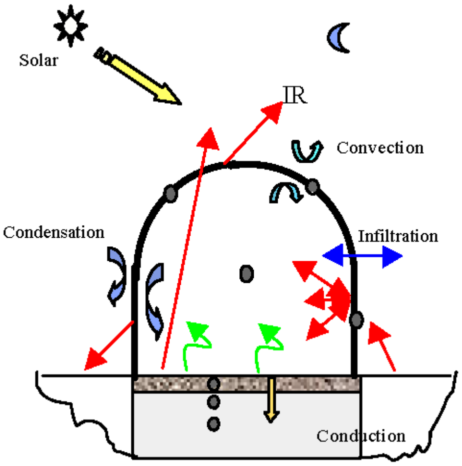

Fig. 2: Heat exchanges between the nodes of the system and the surroundings

greenhouse and for the subsoil have been implemented in the TRNSYS code. The objective is to connect these new modules to the core of the code in order to carry out simulations of the transient behavior of the greenhouse.

To reach this goal, the energy balance equation is established for each component of the shelter: the cover, the inside air, the plants and the soil. In the present study, the cover is divided into six surfaces as shown in Fig. 1. These elements, together with the inside air and the ground, are assimilated to nodes where calculations proceed. In the same manner the subsoil is decomposed into several layers. As shown in Fig. 2, a greenhouse is a system in which all heat transfer modes co-exist, by radiation, convection, with or without phase change and by conduction.

The energy balance equation at each node may be written in the general form provided by Eq. 1:

$$m_i C_i \frac{dT_i}{dt} = \sum Q_i \tag{1}$$

where, m_i is the mass (kg), C_i is the specific heat of air (J/kg/k), T_i is the temperature (K) and Q_i is the sensible/latent heat energy (W). Adapted to the different components of the greenhouse, Eq. 1 may then be written:

For the cover surfaces (i = 1,2,..,6):

$$\rho_i V_i C_i \frac{dT_i}{dt} = Q_i^s + Q_{i,e}^r + Q_{i,j}^r + Q_{ai,i}^{cv} + Q_{ae,i}^{cv} + Q_{ai,i}^1 + Q_{ae,i}^1 \tag{2}$$

For the indoor air sensible heat:

$$\rho_{ai} V_{ai} C_{ai} \frac{dTai}{dt} = Q_{ai,c}^{cv} + Q_{ai,s}^{cv} + Q_{ai,p}^{cv} + Q_{Tae}^{inf} \tag{3}$$

To include the mechanisms of condensation and evapotranspiration on the indoor humidity, an additional energy balance is established for the internal air (Eq. 4):

$$m_{ai} L_v \frac{d\omega_i}{dt} = \sum Q_i^l \tag{4}$$

where, m_{ai} (kg) is the mass of humid air, L_v is the latent heat of water vaporisation (J kg^{-1}) and Q_i^l is the latent heat energy (W) due to condensation on the cover, evapotranspiration and infiltration:

$$\rho_{ai} V_{ai} L_{ai} \frac{d\omega_{ai}}{dt} = Q^1{}_{ai,c} + Q^1{}_{Et} + Q_{\omega ae}^{inf} \tag{5}$$

For the soil surface

$$\rho_s C_{ps} \frac{V_s}{2} \frac{dTs}{dt} = Q_s^s + Q_{s,c}^r + Q_{s,sk}^r + Q_{ai,s}^{cv} + Q_{ai,s}^1 + Q_s^{cnd} \tag{6}$$

For the subsoil nodes (j = 2,... ,N-1):

$$\rho_j C_{pj} V_j \frac{dT_j}{dt} = Q_{j-1,j}^{cnd} - Q_{j,j+1}^{cnd} \tag{7}$$

For the subsoil bottom node, j = N:

$$\rho_j C_{pj} V_j \frac{dT_N}{dt} = 0 \tag{8}$$

where, ρ is the density (kg m^{-3}), C_p is the specific heat (J/kg/k), t is the time, Q^r is the thermal radiative heat transfer, Q^s is the absorbed solar radiation; Q^{cv} is the heat exchanges by convection,

Q_i^{cnd} is the heat transfer by conduction between the soil nodes, Q^{inf} is the indoor-outdoor heat exchange by infiltration and Q^l is the latent heat. The subscripts ai denotes the indoor air, ae the outdoor air, c the cover, e the environment (sky and external soil).

Q^{cv} in Eq. 2 represent the convective heat transfer between the element of cover and both outdoor and indoor air:

$$Q_i^{cv} = h_{ae,i}(T_i - T_{ae}) + h_{ai,i}(T_i - T_{ai}) \tag{9}$$

$Q_{ai,s}^{cv}$ in Eq. 6 represent the convective heat transfer between the soil surface and indoor air:

$$Q_s^{cv} = h_{ai,i}(T_i - T_{ai}) \tag{10}$$

where, $h_{ae,\,i}$, $h_{ai,\,i}$ are the convective heat coefficients between the element of cover and the outdoor and indoor air, respectively and $h_{ai,\,s}$ is the convective coefficient between indoor air and soil.

In the Eq. 8, the heat flux is equal to zero because changes in soil temperature at the deeper layers (>0.3 m) remained almost constant during a day (Gulser and Ekberli, 2004).

Numerical procedure: For numerical analysis, two subroutines have been written in FORTRAN and linked to TRNSYS program.

Simulation tool: The commercially available TRNSYS software was chosen as numerical tools as it offers a flexible environment to carry out transient simulations. This code makes it possible to split complex models into elementary simpler and interconnected modules (Fig. 3). It is therefore, easy for users to add new components to the standard package. In the present study two new modules have been implemented in order to cope with the specificities of the greenhouse system.

- The first one deals with the greenhouse itself: cover, indoor air and soil surface. The model provides information at each time step on the thermal behaviour by calculating the temperature of each component of the greenhouse
- The second one provides temperature profile in the subsoil. The aim of these differentiated modules is to separate the low capacity component of the system (i.e. the greenhouse) from the high capacity component of the system i.e., subsoil. The distinction of different portions of cover following the slope and azimuth solar angle makes it possible to take account of both the incident solar radiation and the wind direction in the convective coefficient determination

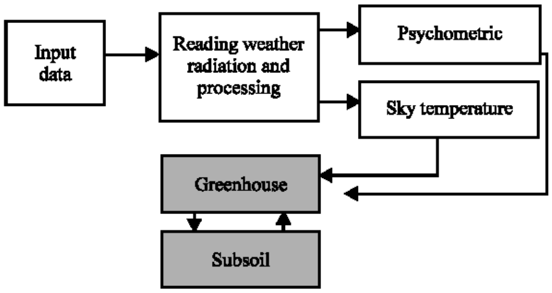

Fig. 3: Flow chart of the greenhouse and subsoil interconnected under TRNSYS environment

Each module is launched independently and coupled with other modules to simulate and solve the entire system problem. The advantage of this procedure comes from the large unit library already implemented that includes some features like physical properties calculators (i.e., psychometric properties), radiation processor, sky temperature and other specific routines to calculate the transmitivity and the view factors for instance.

Numerical technique: The above differential Eq. 2-8 are coupled through energy fluxes. Given these equations are nonlinear with respect to temperatures and humidity. The corresponding system of differential equations can be solved by a Runge-Kutta method (Sharma and Tiwari, 1999). However, the convergence of this method requires a time step $\Delta t \leq m_i\, Cp_i/\Sigma Q_i$ (Klein *et al.*, 2004). For the cover component, of which volume and mass ($m_i = \rho_i.\, V_i$) is very small, the corresponding time step required would be also very small and not convenient for the long time simulation. To avoid this situation, several simplifications were adopted in this study in order to linearize the system of Eq. 2-6. Nonlinear terms were expressed as a function of the mean temperature at the previous time step according to the procedures described by Dos Santos and Mendes (2004).

After linearization the equations are reduced to the flowing first-order differential equation of the form of Eq. 11:

$$\frac{dT_i}{dt} = a_i T_i + \bar{b}_i \tag{11}$$

where, a_i is a constant and $\bar{b}_i$ gathers all terms which depend on the mean temperature or humidity of other nodes:

$$\bar{b}_i = f(\overline{T_j})\ldots j \neq i \tag{12}$$

The modified Euler method (predictor-corrector method) was chosen as numerical method. It is adapted to the present analytical method because the analytic solution is used as prediction step. The combination of these two methods results in the so-called semi-analytical method. It makes the numerical resolution of the equations faster and quite robust (Dos Santos and Mendes, 2004).

Experimental validation: Experiments were conducted inside a tunnel greenhouse at Agrocampus Ouest in Angers (47.43N, 0.55°E) in the West of France. The climate is moderate oceanic. The greenhouse is oriented N-S and covered with a 200 μm thickness plastic film. It is 24 m long, 9 m wide and 5.5 m high with the gutter at 2 m. The greenhouse is maintained closed during two consecutive days (April 21st and 22nd 2010), the soil remained dry and no crop was grown inside the greenhouse during the experiments.

The global solar radiation was measured with a pyranometer (CM-3, Kipp and Zonen, Delft, Netherlands). Wind speed and direction measurements were performed using cup anemometers (HA 430A, Geneq Inc., accuracy 0.11m sec^{-1}), located 10 m above the ground. Dry and wet bulb air temperatures were measured with an aspirated shielded psychrometer (model 225-5230 Assman). The indoor climatic parameters (temperature and relative humidity) were also recorded with a shielded psychrometer every 10 min and 289 observations were collected for each microclimatic parameter.

Measurements were sampled every 10 min by means of a data logger (Delta-T Devices, Cambridge, UK). 289 observations were collected for each microclimatic parameter.

A comparison between calculated and measured values of the indoor temperature, the indoor humidity and the soil temperature was carried out by a regression between calculated and measured data and the Root Mean Square Error (RMSE) were calculated following the Eq. 13:

$$\mathrm{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}(X_m - X_c)^2\right]^{1/2} \tag{13}$$

where, n is number of observation and X_m and X_c is the measured and calculated indoor temperature, the indoor humidity or the soil temperature.

RESULTS AND DISCUSSION

In this study, the model developed under TRNSYS is able to simulate the temporal evolution of three parameters (indoor air temperature, indoor air humidity and soil temperature). The constant parameters used for the numerical study are summarized in Table 1.

The other question studied in this work is the effect of the soil-air convective coefficient correlation (hai, s) on the indoor climate. According to Baille *et al.* (2006), for an air-heated greenhouse and during the night, hai,s varied within a alower and upper limit, corresponding respectively to the functions proposed by de Halleux (hai, s = 1.86 $\Delta.T^{0.33}$) for a greenhouse equipped with heating pipes and Silva cited by Roy *et al.* (2002) (hai, s = 10. $\Delta.T^{0.33}$) for an unheated plastic greenhouse with bare soil). An intermediate correlation was also proposed by Lamrani *et al.* (2001) (hai, s = 5.2 $\Delta.T^{0.33}$) for a greenhouse with a heating floor. In this study, we have examined the effect of these correlations of the combination of these extreme correlations and of the intermediate correlation on the indoor air temperature calculation.

Table 1: Constant parameters used in the simulation

Parameter	Value
Length	24 m
Height at the center	5.5 m
Height at the edge	2 m
Width	9 m
Number of cover surfaces	6
Reflectivity of external soil	0.2
Cover thickness	150 μm
Cover emissivety	0.93
Extinction coefficient of the cover	1650 m^{-1}
Refraction index of the cover	1.515
Volumetric heat capacity of the cover	1795 kJ m^{-3}
Soil reflectivity for visible band	0.2
Soil reflectivity for infrared band	0.1
Soil emissivity	0.8
Soil thickness	0.05
Volumetric heat capacity of the soil	4020 kJ m^{-3}
Heat Conductibility of the soil	0.7 w m^{-1} K^{-1}

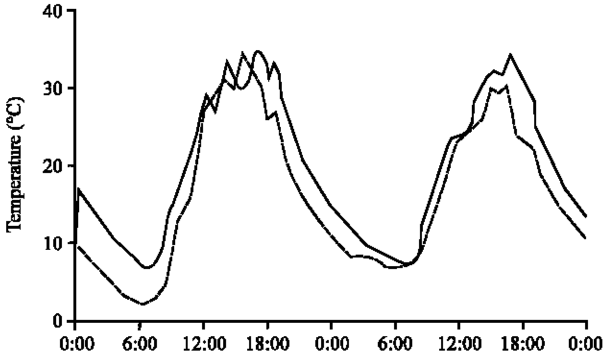

Fig. 4: Calculated (solid lines) and measured (dashed) dynamic changes for indoor temperature, when: hai, s = $10.\Delta.T^{0.33}$

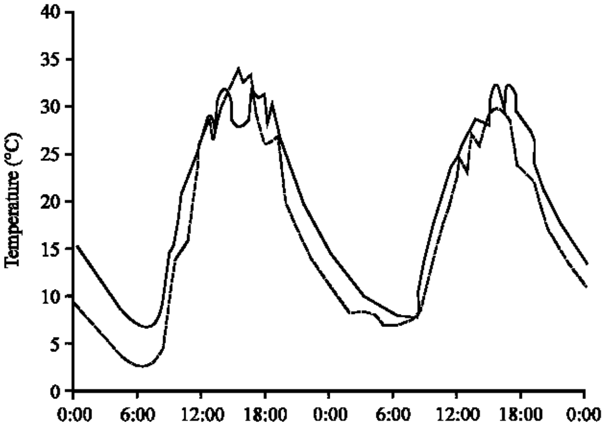

Fig. 5: Calculated (solid lines) and measured (dashed) dynamic changes for indoor temperature, when hai, s = $5.52\ \Delta.T^{0.33}$

Use of upper limit correlation: Using Silva correlation (hai, s = $10.\Delta.T^{0.33}$), the inside air temperature predicted by the model is generally in fair agreement with measurements as indicated in Fig. 4 but appears to be slightly overestimated. The difference may come from the infiltrations. The difference after the peak of temperature is probably due to the use of higher soil-air convective coefficient correlation (hai, s = $10.\Delta.T^{0.33}$)

Use of intermediate correlation: Using Lamrani correlation (hai, s = $5.2.\Delta.T^{0.33}$) to calculate the indoor temperature evolution slightly modifies the results as shown in Fig. 5. The inside air temperature predicted by the model appears to be slightly overestimated and the difference observed is smaller than that observed with Silva correlation.

Use of lower limit correlation: Using de Halleux correlation (hai, s = $1.5.\Delta.T^{0.33}$) to calculate the indoor temperature evolution considerably modify the results as shown in Fig. 6. Inversely to the precedent case, the use of lower correlation is more appropriate after the peak during the cooling period (upward heat flux) but the difference appeared during the warmed period (downward heat flux).

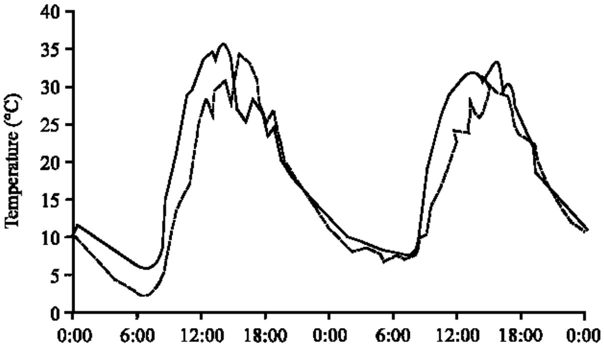

Fig. 6: Calculated (solid lines) and measured (dashed) dynamic changes for indoor temperature, hai, s = $1.86\Delta.T^{0.33}$

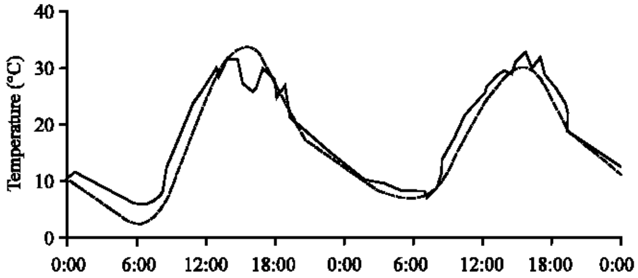

Fig. 7: Calculated (solid lines) and measured (dashed) dynamic changes for indoor temperature, when hai, s = a $\Delta.T^{0.33}$

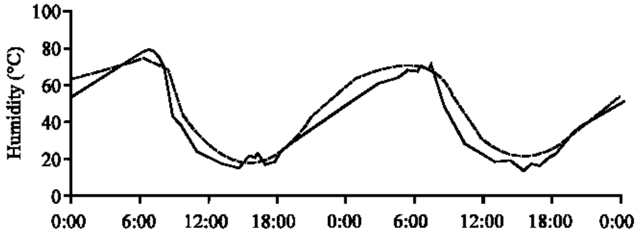

Fig. 8: Calculated (solid lines) and measured (dashed) dynamic changes for indoor temperature, when hai, s = a $\Delta.T^{P}$

From Fig. 5 and 6, it can be seen that the use of the Lamrani correlation is more appropriate undergoing downward heat flux while the use of de Halleux correlation is more appropriate with upward heat flux. As consequence, none of the two extreme correlations can be used to properly and accurately reproduce the measured temperatures over a 24 h period. It appears more advantageous to applies the two correlations with the condition of heat flow direction, one during the warming period (upward heat flux) and the other one during the cooling period (downward heat flux), depending on the direction of heat flow, we propose the general expression: hai, s = $a.\Delta.T^{0.33}$. Where, a = 5.52 if (Ts-Tai) <0 or a = 1.5 if (Ts-Tai)>0).

The results of the corresponding simulations are given in Fig. 7 for the indoor temperature, in Fig. 8 for the indoor humidity and in Fig. 9 for the soil temperature. A comparison between calculated and measured values of the indoor temperature is shown in Fig. 10. The RMSE is 3.34°C.

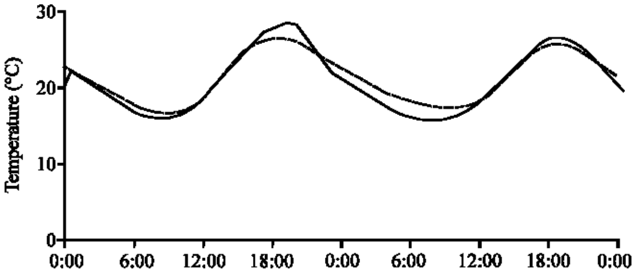

Fig. 9: Calculated (solid lines) and measured (dashed) dynamic changes for soil temperature

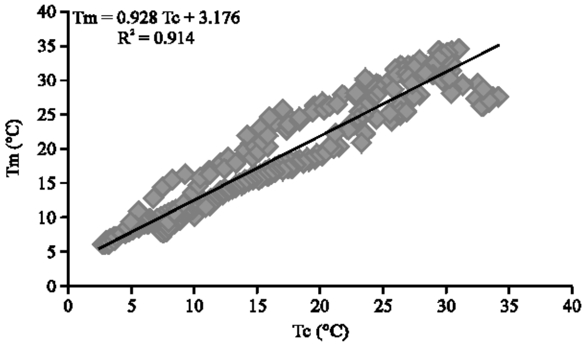

Fig. 10: Calculated indoor temperature (T_c) Vs measured (T_m)

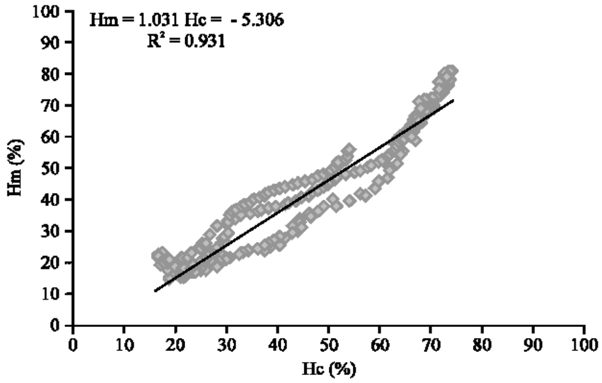

Fig. 11: Calculated indoor humidity (Hc) Vs measured (Hm)

The inside air humidity calculated by the model is in good agreement with measurement as indicated in Fig. 8. The difference may come from infiltrations on the one hand way and from the residual evaporation on the other hand. The comparison between calculated and measured humidity is shown in Fig. 11, the RMSE is 6.72%.

The temperature of the fist subsoil layer calculated by the model is in good agreement with measurement as indicated in Fig. 9. The comparison between the corresponding calculated and measured temperatures is shown in Fig. 12, the RMSE is 0.065°C.

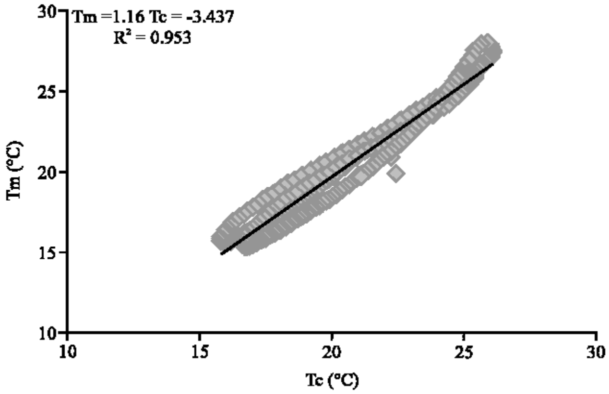

Fig. 12: Calculated soil temperature (Tc) vs. measured (Tm)

CONCLUSIONS

A new model of closed greenhouse climate was developed in the TRNSYS environment to predict the indoor microclimate of a plastic greenhouse. The use of TRNSYS improves the calculation of model inputs.

Based upon the results of the simulation and the experimentation, it was shown that using different expressions of convective heat transfer coefficient between soil and indoor temperature according to the direction of convective heat transfer (from soil to indoor air or vice versa) leads to a better accuracy of the predicted indoor climate. We propose the more general expression of convective heat transfer coefficient between soil and indoor temperature valid all a day long.

The developed models of closed greenhouse and subsoil can be used for any size with different characteristics of cover and soil but improvements are still needed concerning the case of ventilated greenhouses. Further modelling efforts are also required to integrate a more accurate soil model taking account of the variations of the soil properties with soil moisture profile and texture.

ACKNOWLEDGMENT

The authors are indebted to the EPHor (Environmental Physics and Horticulture) research Unit of Agrocampus Ouest for their invaluable support.

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