GREENHOUSE CROP TRANSPERSION MODEL FROM EXTERNAL CLIMATE CONDITIONS

T. Boulard and S. Wang
I.N.R.A. - Station de Bioclimatologie - Site Agroparc, Domaine Saint Paul, 84914 Avignon Cedex 9, France

Keywords: Greenhouse, crop, transpiration, model, climate, tomato, ventilation

Abstract

A new and simple greenhouse crop transpiration model enabling predictions from outdoor conditions is presented and the parameters involved are discussed with respect to different types of greenhouse-crop systems. This transpiration model was validated against experimental data measured in a tomato crop cultivation in Avignon in (i) warm conditions and (ii) cold conditions when the greenhouse air was confined. The model estimation improved from cold to warm conditions. Comparisons with previous transpiration models have shown a deterioration of the transpiration model performances when greenhouse air was confined. However, model performance was satisfactory when, as is often the case in Mediterranean countries, the greenhouse air was closely coupled to outdoor conditions.

1. Introduction

Previous steps in the development of physically based models of greenhouse crop transpiration considered the water vapour exchange between the protected canopy and the inside air. Transpiration models with the greenhouse climate as a boundary condition were first developed in the northern regions of Europe and North America for horticultural crops: tomato (Stanghellini, 1987; Jollet & Bailey, 1992), cucumber (Yang et al., 1990), lettuce (Pollet et al., 1999). In these northern conditions, the glasshouse is generally poorly ventilated during a large part of the growing season. The boundary layer conductance over glasshouse crops tends to be much smaller than would be expected for similar crops growing outdoors. Thus, glasshouse crops are very strongly decoupled from the outside atmosphere by the presence of the glass, and the heat and the water released at crop surface will accumulate inside the glasshouse. Consequently, the transpiration rate will adjust until it reaches a stable equilibrium transpiration rate dictated by the net radiation received (Jarvis, 1985). On the contrary, greenhouse crop transpiration in Mediterranean or warm conditions is much more dependent on convective transfers. As the ventilation and the turbulent mixing are vigorous, the saturation deficit at the leaf surface is closely coupled to the deficit of ambient air, and the latter is directly influenced by the outdoor saturation deficit and represents about 40% of the total transpiration for a May-June greenhouse tomato crop in the South of France (Jemaa, 1995) and both radiative and advective components of transpiration must be considered in models (Boulard et al., 1991; Papadakis et al., 1994).

From an operational point of view, the calculation of greenhouse crop transpiration from outside climate is interesting. This is the case in Mediterranean countries where the part of transpiration dependent on the air saturation deficit can hardly be estimated because the greenhouses consist of simple shelters, such as tunnels or wooden structures, seldom equipped with inside climate-sensors, which allow calculation of crop transpiration. There are real needs for greenhouse crop transpiration models enabling simulations based on outdoor conditions and, in this paper, we shall derive the
basic equations for greenhouse crop transpiration and the model will be tested against measured data for a tomato crop in both winter and summer conditions.

2. Theory

2.1. Derivation of crop transpiration with respect to external climatic parameters

The greenhouse-crop system can be considered as a solar collector involving both sensible and latent heat exchanges and its thermal performances can be described in a similar way by the use of a single energy balance equation (Okano et al., 1985; Seginer & Albright, 1983; Boulard & Baille, 1993). The greenhouse energy balance can be written

\[ \lambda E + H = \alpha R_g + Q_h - G - C \]  

(1)

The main parameter involved is the solar efficiency factor (\( \alpha \)). \( E \) is the canopy transpiration (kgm\(^{-2}\)s\(^{-1}\)), \( \lambda \) the latent heat of water vaporisation (Jkg\(^{-1}\)), \( H \) the sensible heat exchange by ventilation (Wm\(^{-2}\)), \( R_g \) the outside global solar radiation (Wm\(^{-2}\)), \( Q_h \) the heating flux density (Wm\(^{-2}\)), \( G \) the heat storage or retrieval rate of the greenhouse-soil system (Wm\(^{-2}\)). \( C \) (Wm\(^{-2}\)) is the sensible heat loss through the cover (C= K\( \Delta T \)), where \( K \) is the overall energy loss coefficient (Wm\(^{-2}\)) and \( \Delta T \) the air temperature difference between inside and outside (K). The latent heat exchange due to canopy transpiration can be expressed with respect to the difference of air humidity between indoors and outdoors:

\[ \lambda E = K_v \Delta e \]  

(2)

where \( \Delta e \) is the water vapour pressure difference between the interior and exterior air (Pa) and \( K_v \) is the latent heat transfers coefficient (Wm\(^{-2}\)Pa\(^{-1}\)). The sensible heat exchange can also be expressed with respect to the difference of air temperature between indoor and outdoor:

\[ H = K_H \Delta T \]  

(3)

where \( K_H \) is the sensible heat transfer coefficients (Wm\(^{-2}\)K\(^{-1}\)). Greenhouse crop transpiration can be deduced from the greenhouse available energy (\( \lambda E + H \)) and from the inside air saturation deficit \( D_i \) (Pa), by means of the Penman-Monteith (PM) formula:

\[ \lambda E = \frac{\delta(\lambda E + H) + 2LAIpC_pD_i / r_s}{\delta + \gamma(1 + r_s / r_a)} \]  

(4)

where \( C_p \) and \( \rho \) are the specific heat of air at constant pressure (Jkg\(^{-1}\)K\(^{-1}\)) and the air density (kgm\(^{-3}\)), \( \gamma \) is the psychometric constant (PaK\(^{-1}\)), \( \delta \) is the slope of the water vapour saturation curve (PaK\(^{-1}\)), \( r_s \) and \( r_a \) are the aerodynamic and stomatal resistances of the leaves (s\(^{-1}\)) and LAI is the leaf area index (-). The water vapour pressure deficit of the interior air (\( D_i \)) can be expressed as a linear function of the water vapour pressure deficit and temperature of exterior air, \( D_o \) and \( T_o \):

\[ D_i = \delta(T_o)(T_i - T_o) - \Delta e + D_o \]  

(5)

where \( \delta(T_o) \) is the slope of the water vapour saturation curve at \( T_o \) (PaK\(^{-1}\)). The above system constitutes a linear system of five equations with five unknowns (\( \lambda E \), \( H \), \( D_i \), \( \Delta T \) and \( \Delta e \)) which can be solved analytically. Consequently, \( \lambda E \) can be expressed with respect to the outside climate and greenhouse-crop parameters:
\[ \lambda E = \frac{\alpha R_g + Q_h - G + \frac{(K + K_H)K_2}{K_1K_H + K_2\delta}D_o}{1 + \frac{(K + K_H)(1 - K_1 + K_2/K_v)}{K_1K_H + K_2\delta}} \]  

(6)

with

\[ K_1 = \frac{\delta}{\delta + \gamma(1 + r_s/r_a)} \]  

(7)

and

\[ K_2 = \frac{2LAIpC_p/r_a}{\delta + \gamma(1 + r_s/r_a)} \]  

(8)

2.2. Parameters estimation

The solar heating efficiency of the greenhouse (\( \alpha \)) is a key factor that strongly modulates the influence of solar radiation (Seginer & Albright, 1983, Boulard & Baille, 1993). It can be deduced from the greenhouse energy balance (1) over 24-hour periods:

\[ \Sigma\lambda E + \Sigma H = \alpha\Sigma R_g + \Sigma Q_h - \Sigma G - \Sigma K \Delta T \]

Assuming that the sum of soil heat storage and retrieval (\( \Sigma G \)) is approximately null over a 24-hours period, we get a simple formula enabling the identification of \( \alpha \):

\[ \alpha = \frac{\Sigma(\lambda E + H - Q_h + K \Delta T)}{\Sigma R_g} \]  

(9)

The overall energy loss coefficient can be considered as dependent on external wind speed \( V \) (ms\(^{-1}\)) following the simple relation (Bailey & Cotton, 1980):

\[ K = A + BV \]  

(10)

Where \( A \) and \( B \) depend on the greenhouse design (ratio of the soil surface, on the greenhouse cover: \( S_o/S_c \)), on the type of the cover material (glass, polyethylene, PVC) and the presence of a single or double cover. The coefficients for the transfer of sensible and latent heat by ventilation, \( K_H \) and \( K_V \), are proportional to the ventilation flux, \( \phi_v \) (m\(^3\)s\(^{-1}\)). Ignoring buoyancy forces, the latter can be considered to be linearly dependent on the vent opening area and wind speed (Boulard & Baille, 1995; Kittas et al., 1995):

\[ \phi_v = \frac{S_o}{2C_d}\sqrt{CV} \]  

(11)

where

\( C \) is a wind related efficiency coefficient (-)
\( C_d \) is an average vent discharge coefficient (-)
\( S_o \) is the vent opening area, m\(^2\)

So, we obtain:

\[ K_H = \frac{\rho C_p \phi_v}{A_g} \quad \text{and} \quad K_V = \frac{\lambda e_p \phi_v}{A_g} \]
where \( A_g \) is the greenhouse ground area (m²), \( \xi \) the conversion factor between the air water vapour content (kg\( \text{kg}_{\text{g}}^{-3} \)) and the air water vapour pressure (Pa), \( 6.25 \times 10^{-6} \text{ kg}_{\text{g}} \text{kg}_{\text{g}}^{-1} \text{ Pa}^{-1} \).

The following relation (Alt, 1978) gives the slope of the water vapour saturation curve to the temperature:

\[
\delta = \frac{2504000}{(T - 35.86)^2} e^{\frac{17.27(T - 273.15)}{T - 35.86}}
\]  

(12)

According to Avissar et al. (1985), the stomatal resistance can be considered to be dependent on the inside level of global radiation and inside air temperature and humidity based on exponential laws. For greenhouse tomato crops, the effects of radiation on stomatal resistance is the most crucial and obeys the following relation (Boulard et al., 1991):

\[
r_s = 200 \left( 1 + \frac{1}{\exp(0.05(\tau R_g - 50))} \right)
\]  

(13)

where \( \tau \) (-) is the transmittance of the greenhouse cover. The aerodynamic resistance, \( r_a \), mainly depends on the aerodynamic regime that prevails in the greenhouse. If we consider that the buoyancy force can be ignored with respect to the wind force, \( r_s \) can be directly expressed with respect to the average interior air speed:

\[
r_a = \frac{220}{V_i^{0.8}}
\]  

(14)

where \( d \) is the characteristic length of the leaf (m). \( V_i \), the mean interior air speed (ms\(^{-1} \)), can be considered to be proportional to the ventilation flux \( \phi \), divided by \( A_c \) (m\(^2 \)), the vertical cross section area perpendicular to the average direction of the inside air flux, in this case the greenhouse axis (Wang et al., 1999):

\[
V_i = \frac{\phi}{A_c}
\]  

(15)

3. Materials and methods

3.1. Greenhouse and experimental set up

The study was carried out from March to June in a climate controlled bi-span plastic-house equipped with both heating and cooling devices. The greenhouse was 32 m long in the north-south direction and consisted of two spans, 6.5 m width each. The mean height was 4 m. Two vents, each 1.06 m wide, ran the length of the entire greenhouse near the gutters. The ratio of the total vent area to ground area was 0.32. Maximum vent opening angle was 58 degress.

Tomato plants, c.v. Rondello, were planted (density = 2 plants/m\(^2 \)) in January and grown on rockwool slabs placed on a white plastic mulch. The heating and ventilation set points were approximately 17 °C and 22 °C respectively. The leaf area index (LAI) was estimated each month from measurements of leaf dimensions.
3.2. Climatic and transpiration measurements

Inside and outside climate variables, dry and wet bulb temperatures and global radiation were monitored at hourly time increments, together with the state of the vent openings and the heating consumption. Crop transpiration was determined by means of a weighing lysimeter (maximum load 120 kg, precision ± 10 g) supporting four plants. All the measurements were sensed every minute, averaged on an hourly basis and stored in a data logger.

4. Results and discussion

All the forthcoming results were determined using data collected during two successive years: 1991 and 1992. The solar efficiency of the greenhouse, \( \alpha \), was determined using the data from spring 1991 and the transpiration model was validated against the transpiration measurements collected during the spring of 1992. Data from individual ventilation experiments performed over several years were also used for the identification of the parameters of the ventilation model (Boulard, 1993).

4.1. Solar efficiency, \( \alpha \)

The daily course of the identified value of \( \alpha \) (Eq. 14, with \( K=6+0.5V \)) from April 7 to May 4 is given in Fig. (1). It averaged \( \alpha=0.59 \) (with \( \sigma=0.05 \)), to be compared with \( \alpha=0.50 \), found in a 7 m tunnel occupied by a young tomato crop (Sbita et al., 1998), or \( \alpha=0.56 \) for a single glazed greenhouse (Garzoli, 1985).

4.2. Crop transpiration

Assuming that G was negligible with respect to the other terms of the heat balance and using the identified value of solar efficiency (\( \alpha=0.59 \)), the transpiration model was validated with respect to two types of climatic conditions: i) summer or late spring climatic conditions, when the coupling between the greenhouse crop and the outside climate was important and ii) winter or early spring climatic conditions, when the greenhouse was not ventilated and the inside air strongly confined. Calculated versus measured greenhouse crop transpiration fluxes together with their regression lines and statistical parameters are given on an hourly basis in Figs (2) and (3) for the periods May 1-31, 1992, and March 10-31, 1992, respectively. This model was developed for summer conditions and model estimation improved from March to May, as seen by the increase of the slope of the regression line and by the improvement of the correlation coefficient. The standard deviations are similar in March and in May (23 Wm\(^{-2}\)) and the slopes of the regression lines are always lower than 1, especially in March, which indicates that the model systematically underestimates the transpiration fluxes.

The hourly courses of measured and computed transpiration fluxes are shown in Figs (4) and (5) for the May and March periods respectively. In May, a good fit between measured and simulated data can be observed in both diurnal and nocturnal periods and the precision of the model is similar on sunny days (corresponding to the days with high transpiration fluxes) and overcast days (corresponding to the days with low transpiration fluxes).

Larger discrepancies are noticed in March during night-time when the greenhouse was closed and when the heating system was systematically activated. A similar deterioration of model performances can also be observed in daytime when the transpiration flux was weak, as was the case during cloudy days (corresponding to the days with low transpiration fluxes).
4.3. Comparison with previous models

Using the same experimental data, this model can also be compared with previous greenhouse crop transpiration models based on the Penman-Monteith formula and considering only inside climate (Jemaa, 1995). The regression lines between measured and calculated transpiration fluxes and the associated statistical parameters for the May and March periods are shown in Table 1. It is clear that considering outside climate instead of inside climate as a boundary condition implies a deterioration of transpiration model performance. However, in May we observed only a slight underestimation and loss of prediction of the model, while in March the underestimation of the transpiration fluxes reached almost 20% and the $R^2$ decreased by 0.1 with respect to the March value.

4.4. Model limits

The deterioration of the model performances detected in winter and early spring is mainly due to several simplifications introduced during the model derivation.

The evapo-condensation phenomena on the greenhouse cover, particularly important when the greenhouse is closed, are not considered in the water vapour balance described by relation (2).

Relation (5) allowing for the derivation of the water vapour pressure deficit of inside air ($D_i$) as a linear function of the water vapour pressure deficit and temperature of the exterior air, $D_o$ and $T_o$, is verified only when $e_s(T_i) - e_s(T_o) \approx 8(T_o - T_i)$, i.e. when $T_i$ is not too far from $T_o$. This is not the case during winter when the greenhouse is heated. These two reasons could explain the majority of the discrepancies. However, other causes, due to the ventilation model, must also be examined.

Linearisation of the model requires a linear relationship describing ventilation. That is why relation (11) neglects the buoyancy forces linked to $(T_i - T_o)$, though these forces can be significant, particularly when $(T_i - T_o)$ is high ($T_i - T_o > 5^\circ C$) and $V$ is low ($V < 1.5 \text{ m s}^{-1}$).

No leakage model was considered in our description of the air exchange rate and this can also explain a large part of the differences observed between simulations and measurements at night-time. All these errors occur when the greenhouse is closed, but their magnitude is not significant because the transpiration fluxes are generally weak at that time. They could also be corrected but this would detract from the simplicity and robustness of this new model.

5. Conclusions

A new greenhouse crop transpiration model enabling predictions from outdoor conditions is derived and the parameters involved are discussed with respect to the different types of greenhouse-crop systems.

Testing of the model in summer and winter conditions shows that model predictions improve from March to May and from nocturnal to diurnal periods. The deterioration of model performance detected in winter and early spring is mainly due to simplifications introduced during model derivation. Nevertheless, such deterioration mainly occur when the greenhouse is closed and generally when the transpiration fluxes are weak. Finally it appears that the errors observed when the greenhouse is closed could be corrected, but that such modifications would detract from the model’s simplicity and robustness. It is also shown that this transpiration model is designed to be used with simple shelters when inside conditions are closely coupled to outside ones, as is the case in Mediterranean conditions during most of the year. In addition to the direct estimation of crop transpiration, this model could also be considered to determine inside air temperature and humidity. It could be combined with models of cropping system behaviour using outside climate as boundary conditions.
References


Kittas C., Draou B., Bouard T., 1995. Quantification du taux d'aération d'une serre a ouvrant continu en toiture – Agric. and Forest Meteorol. , n° 77, 95-111


Tables

1. Comparison of the regression lines and associated statistical parameters between the measured greenhouse crop transpiration and simulations performed by the present model and a previous model with inside climate as boundary conditions (Jemaa, 1995).

<table>
<thead>
<tr>
<th>Transpiration model</th>
<th>May 1-31, 1992</th>
<th>March 10-31, 1992</th>
</tr>
</thead>
<tbody>
<tr>
<td>Previous model: PM &amp; inside climate</td>
<td>$\lambda E_{cal} = 1.01 \lambda E_{meas} + 4.45, \sigma = 13 \text{ Wm}^{-2}$, $R^2 = 0.99$</td>
<td>$\lambda E_{cal} = 1.03 \lambda E_{meas} + 4.4, \sigma = 9.2 \text{ Wm}^{-2}$, $R^2 = 0.99$</td>
</tr>
<tr>
<td>Present model: PM &amp; outside climate</td>
<td>$\lambda E_{cal,o} = 0.95 \lambda E_{meas} + 7.46, \sigma = 23 \text{ Wm}^{-2}$, $R^2 = 0.97$</td>
<td>$\lambda E_{cal,o} = 0.85 \lambda E_{meas} + 14.27, \sigma = 23.4 \text{ Wm}^{-2}$, $R^2 = 0.89$</td>
</tr>
</tbody>
</table>

Figures

1. The greenhouse solar efficiency ($\alpha$) as a function of time. April 7 to May 4, 1991
2. Calculated (present transpiration model) versus measured (lysimeter measurement) values of greenhouse crop transpiration rate. May 1992, hourly basis, the solid line represents the regression line.

3. Calculated (present transpiration model) versus measured (lysimeter measurement) values of greenhouse crop transpiration rate. March 1992, hourly basis, the solid line represents the regression line.
4. Time courses of (---) measured (lysimeter measurement) and (—) calculated (present transpiration model) values of tomato crop transpiration rates. May 1992, hourly basis.

5. Time courses of (---) measured (lysimeter measurement) and (—) calculated (present transpiration model) values of tomato crop transpiration rates. March 1992, hourly basis.