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Modeling of the Climate for a Greenhouse in the North-East of México

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Abstract: Climate control is one of the principal reasons to use a greenhouse. The efficiency of the control depends of the precision of the model that better describes the dynamics variables inside the greenhouse. Is presented a modification of a climate model in an greenhouse in order to include the effects of: air density variations due to humidity changes, the humidity addition by nebulizers, the use of shade cloths and the use of forced ventilation. Such effects are required for greenhouses located in the north-east region of México, because the warm extreme climate makes the use necessary of these elements like economic resources of cooling, being essential to include in the model the above mentioned effects. The introduced modifications are validated by comparisons between real measurements carried out in a greenhouse in this region of México through of simulations. The results in section 5 show that the proposed model has a better behavior when effects mentioned are included on sections 3 and 4.

Keywords: Modelling and control of agriculture, Greenhouse control, Nonlinear systems, Greenhouse climate, Shade cloths, Air density, Added humidity, Validation.

1. INTRODUCTION

The purpose of the greenhouses, or farming protected, is to try to maintain an independent interior climate to the one of the exterior, that they are economically profitable and appropriate for the development and growth of the plants. These structures are designed and equipped in direct function to the existing environmental conditions in the zone where the greenhouse is located. The equipment, form and present elements in the greenhouse will depend on how different it is the climate in the outside against the requirements of the plant for its development. In such way that, a climatic model will have to be elaborated and adjusted to the equipment and present conditions in the climatic zone where it is. In this context the necessary actions were made to obtain a climate model for a greenhouse located in the northeast of México, in Marín Nuevo León, where the climate is catalogued like extreme [Sintesis Geo.México [1981]] because thermal differences (monthly average) surpass the 7 ^oC.

2. ANTECEDENTS

The present work starts in a dynamic climate model in greenhouse presented by [Leal Iga J. et al. [2006]], which takes into account the effect of the variability of the density of the air due to changes in the humidity, being an important factor because in the climatic zone where is the greenhouse of Marín N.L is common the use of humidifiers (fogging systems) for cooling, who add important humidity quantities to the inside atmosphere. In addition, in the development of this work, the effects of shade cloths and forced ventilation were added to the model, due to the presence of these equipments in the greenhouse studied.

The work of [Leal Iga J. et al. [2006]] takes as base the development of [Frank Tap F. [2000]] which is the result of a sequence of investigations and improvements to a climate model made in the Dutch school of Wageningen, which began at the beginning of the 80s with the seminal developments of [Bot G. [1983]] and [Udink ten Cate A.J. [1983]]. In both models are considered equations for the temperature within the greenhouse, and including the effect of the heating and the opening of windows. Moreover, they consider the greenhouse is like a completely mixed tank, in which the climatic variables are uniform. The model of [Bot G. [1983]] handles a great number relatively of variables of state due to the consideration of different ground layers. The model of [Udink ten Cate A.J. [1983]] takes into account in an empirical way the effect of radiation and the heat due to the evaporation by crop, avoiding the necessity of the long wave radiation forecast in the atmosphere for the calculus.

This model is obtained by the linearization process in the vicinity of a work point, and by this supposition it changes to a process of first order. In a later development [Tchamitchian M. et al. [1992]] despise the dead times in the model of [Udink ten Cate A.J. [1983]] and thus they simplify the representation of the heat entrance to the greenhouse. Van Henten incorporates more accurate calculations for the respiration, transpiration and photosynthesis. As well as the incorporation to the model of improved equations for the air interchange with the outside [Van Henten, E.J. [1994]]. Frank Tap improves the model when including the effect of the air humidity within the greenhouse, as well as a more accurate ventilation modelling [Frank Tap F. [2000]].

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In this research, the pursuit goal is to obtain a model that adds the effects and the more relevant elements that are present in the greenhouse of Marín N.L. and thus to count with a model of the climate inside of greenhouse that better adjusts to the reality and to use it in a future on the climate control.

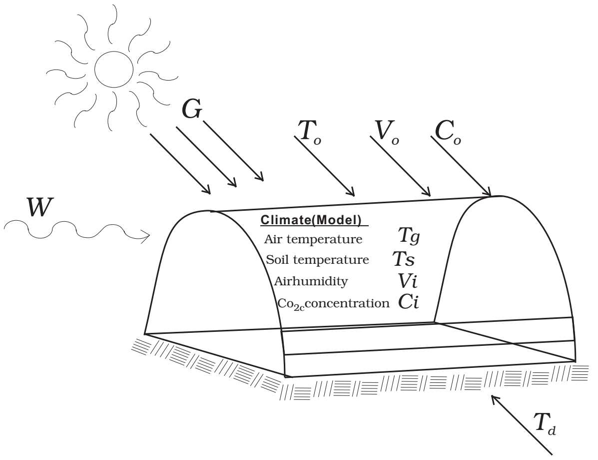

Fig. 1. Variables in the greenhouse system

3. GREENHOUSE CLIMATE MODEL TAKEN FROM BASE

The starting point of this work is the model proposed by [Leal Iga J. et al. [2006]], which is based on the developed by [Frank Tap F. [2000]], that is a very complete model because it is the result of the contributions done by himself [Frank Tap F. [2000]] and other investigators of the Dutch school of Wageningen [Udink ten Cate A.J. [1983]], [Tchamitchian M. et al. [1992]]. In this way, the model of [Frank Tap F. [2000]] will be shown in first part in the development of the research. The taken model as base is formed of four differential equations which consider the variations in the inside greenhouse, corresponding to: the temperature of the air, the temperature of the ground, air humidity, and CO_2 concentration, Fig.1.

Temperature of the air inside the greenhouse

The equation for temperature of the air considers the effect due to the following influences: the interchange of heat between the outside and inside of the greenhouse; between the ground and the air within the greenhouse; between the air inside and the pipe of the heating system; between the roof and the air inside; the influence of sun radiation; the loss of heat by transpiration of the plant; the gain of heat by the condensation of the water steam in the roof. The corresponding equation is as follows:

$$\begin{aligned} C_g \frac{dT_g}{dt} &= K_v(T_o - T_g) + K_r(T_o - T_g) + \\ &K_s(T_s - T_g) + \alpha(T_p - T_g) + \\ &\eta G - \lambda E + \frac{\lambda}{\epsilon + 1} M_c \end{aligned} \tag{1}$$

The description of all variables and the values of the parameters can be found in the Appendix A and in [Leal Iga J. et al. [2006]]. The algebraic equations of the parameters are listed in Appendix B. It is important to clarify that K_r is a coefficient of conduction of heat transfer. K_v, K_s and α are coefficients of convection of heat transfer.

Temperature of the soil inside the greenhouse

The differential equation considers: the heat interchange between the inner air of the greenhouse and the soil, and the interchange between the superficial soil and the deep soil. The corresponding equation is:

$$C_s \frac{dT_s}{dt} = -K_s(T_s - T_g) + K_d(T_d - T_s) \tag{2}$$

CO_2 Concentration

The differential equation of CO_2 is formed by the balance of mass between CO_2 of the interior and the outside; the flow of CO_2 injection, the photosynthesis of the crop, and the CO_2 that was contributed by the respiration. The corresponding equation is:

$$\frac{V_g}{A_g} \frac{dC_i}{dt} = \phi_v(C_o - C_i) + \varphi_{inj} + R - P \tag{3}$$

Air water vapor concentration in the greenhouse

The air water vapor concentration in the greenhouse considers the effect of the balance of mass between the inside and the outside; the transpiration of the crop; as well as the condensation effect. The corresponding equation is:

$$\frac{V_g}{A_g} \frac{dV_i}{dt} = E - \phi_v(V_i - V_o) - M_c \tag{4}$$

The meaning of the variables, states and parameters can be found in the Appendix A and in [Leal Iga J. et al. [2006]].

4. ADDITION OF THE EFFECTS REQUIRED FOR ADJUSTING THE MODEL TO THE CONDITIONS OF THE GREENHOUSE OF MARÍN N.L.

The model shown in the previous section, equations (1), (2), (3), and (4) were developed for a greenhouse Dutch located in a cold climate most of the year and therefore with different requirements in equipment to those of the greenhouse of Marín. In order to obtain a model that better adjusts to the existing conditions in the greenhouse of Marín N.L., in the present work was added the effects of:

a) The variability of the air density because of changes in humidity.
b) The humidifiers (nebulizers).
c) The forced ventilation.
d) The shade cloths.

a) Addition of the effect of variability of the air density due to changes in humidity.

In the work of [Leal Iga J. et al. [2006]] was taken the model as base of [Frank Tap F. [2000]] and was added the effect of the variability of the air density due to the changes in humidity . Thus, in [Leal Iga J. et al. [2006]] was considered the air density M_{air} as the mass division of molecules of dry air m_{dry} plus the mass of molecules of water vapour in the air m_{water_vap}, divided by the volume that contains them $Volume$. Measured like $\frac{Kg}{m3}$.

This implies that the density of the air is evaluated as:

$$M_{Air} = \frac{m_{air}}{Volume}$$
$$M_{Air} = \frac{m_{dry}}{Volume} + \frac{m_{water\_vap}}{Volume}$$

$$M_{Air} = \gamma_o + V_i \tag{5}$$

where:

γ_o	Dry air density, in $\frac{Kg}{m3}$ and it represents the mass of the dry air per volume unit at a specific temperature of 20 C. This value is considered constant.
V_i	Humidity concentration inside the greenhouse, in $\frac{Kg}{m3}$ and it represents the mass of water vapour per unit of volume. This value changes with time, calculated by the equation (4)

In this way, the density of air M_{air} considering the effect of humidity is evaluated as the variation in the concentration of water vapour by means of the equation (4).

When applying the equation (5) in the equations (B.2) and (B.3), which are the terms that are affected when considering not-constant the density of the air, result in:

- Coefficient of heat transference by ventilation.

$$K_v(t) = (\gamma_o \cdot c_p + V_i(t) \cdot C_H)\phi_v \tag{6}$$

- Heat capacity of the air inside the greenhouse

$$C_g(t) = c_p \cdot h \cdot \gamma_o + C_H \cdot h \cdot V_i(t) \tag{7}$$

where C_H is the specific heat of water vapor, at constant pressure. Applying the equation (7) in the equation (1), deriving and it simplifying, it would be:

$$\begin{aligned}\frac{dT_g}{dt} = \frac{1}{h(c_p\gamma_o + C_H V_i)} & [K_v(T_o - T_g) + \\ & +\alpha(T_p - T_g) + K_r(T_o - T_g) + \\ & K_s(T_s - T_g) + \eta G - \lambda E + \frac{\lambda}{\epsilon + 1}M_c \\ & -C_H T_g(E - \phi_v(V_i - V_o) - M_c)]\end{aligned} \tag{8}$$

The equation (8) considers the variations in the humidity of the air.

b) Addition to the model the effect of humidity added by nebulizers.

The humidity added towards the interior of the greenhouse by the nebulizers will be calculated like:

$$Q = \begin{cases} \frac{\rho \cdot Q_f}{A_g} \quad if \ (\frac{2.16 \cdot P_c^*}{T_o + 273.15} - V_i) > \rho \cdot Q_f \cdot dt \\ 0 \quad\quad\ if \ (\frac{2.16 \cdot P_c^*}{T_o + 273.15} - V_i) < \rho \cdot Q_f \cdot dt \end{cases} \tag{9}$$

where:

Q	Humidity added by the nebulizers, in $\frac{Kg}{s \cdot m^2}$
Q_f	Water consumption by the nebulizers, in $\frac{m^3}{s}$
A_g	Greenhouse area, in m^2
ρ	Specific mass of water, in $\frac{Kg}{m^3}$

Adding to the equation differential of the humidity variation inside the greenhouse (4) the effect of the humidity added by the nebulizers (9), it would be:

$$\frac{V_g}{A_g}\frac{dV_i}{dt} = E - \phi_v(V_i - V_o) - M_c + Q \tag{10}$$

In this way, the equation (10) is in conditions for the modelling the effect of the nebulizers.

c) Addition to the model the effect of forced ventilation.

The effect of forced ventilation will be inscribed in the equation of flow ventilation (B.4), as ϕ_{fan}, resulting in:

$$\phi_{vent} = (\frac{\sigma r_{wl}}{1 + \chi r_{wl}} + \zeta + \xi r_{ww})W + \psi + \phi_{fan} \tag{11}$$

d) Addition to the model the effect of the shade cloths

The effect of the shade cloths will be added in the model by means of a reduction factor of solar radiation intensity Z. This factor will be applicable in the equations (8) and (B.1), as:

$$Z\eta G \tag{12}$$

Fig. 2. Nebulizer, shade cloth and greenhouse in Marín N.L.

where:

Z	Effective solar radiation transmission trough shade cloths
η	Parameter of radiation
ρ	Solar radiation $\frac{watts}{m^2}$

then, the modified equations would be:

$$\begin{aligned}\frac{dT_g}{dt} = \frac{1}{h(c_p\gamma_o + C_{htb} V_i)} & [K_v(T_o - T_g) + \\ & +\alpha(T_p - T_g) + K_r(T_o - T_g) + \\ & K_s(T_s - T_g) + Z\eta G - \lambda E + \frac{\lambda}{\epsilon + 1}M_c \\ & -C_{htb} T_g(E - \phi_v(V_i - V_o) - M_c)]\end{aligned} \tag{13}$$

$$E = W_L \frac{qS_n Z\eta G + r\rho c_p D_g g_b}{\lambda(S + \gamma(1 + \frac{g_b}{g})} \tag{14}$$

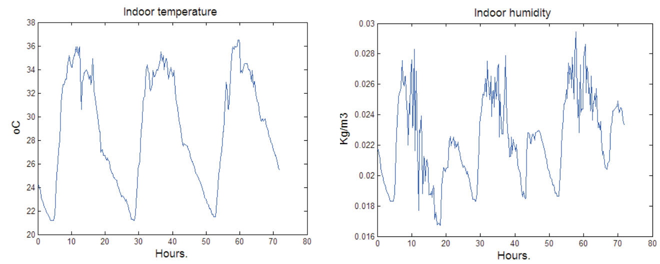

Fig. 3. Indoor data

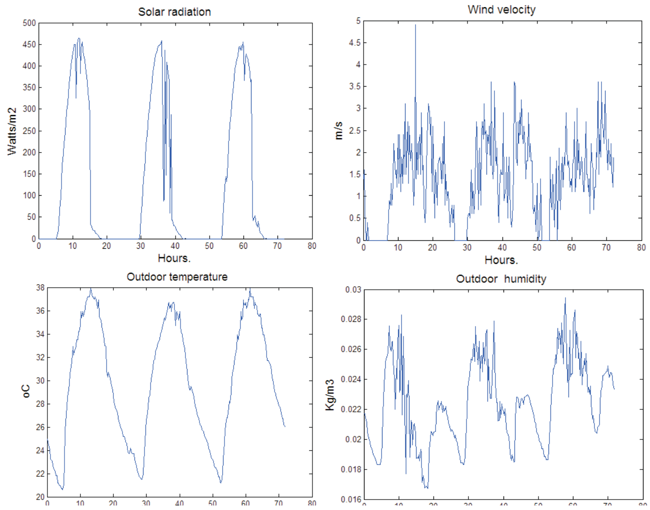

Fig. 4. Outdoor data

5. DATA MEASURED IN THE GREENHOUSE OF MARÍN N.L.

The greenhouse, nebulizer and shade cloth are shown in the Figure 2. The greenhouse has 50 mts. length, 21 mts. of width, and 4.35 mts. of height until the lintel. The cover has a parabolic form and is oriented towards the north-south. The structure is of tubes of galvanized steel and the cover is of polypropylene in four spaces. It is equipped with 4 nebulizers, one in each side, and eight inner ventilators, one in each end of the clear spaces. Moreover, the greenhouses count with zenithal windows and lateral windows of rolled up plastic, all equipped with meshes anti-insects. Four fans extractors in the north wall operating continuously all day and night. Due to the requirements of cooling, this factor induces a strong effect above all other factors. During the investigation, crop of tomato in the greenhouse was had. The measurements were made with two meteorological stations, 540-A handar U.S. model, one in the inside of the greenhouse to measure the temperature of the air and relative humidity, and the other one was in the outside, to measure solar radiation, wind speed, relative humidity and temperature.

The measured data are displayed in Figures 3 and 4.

6. VALIDATION OF THE MODEL MODIFIED TO ADJUST AT THE CONDITIONS OF THE GREENHOUSE IN MARÍN N.L.

For the validation, the main idea is to compare the dynamic behavior of both models, from the original one taken as base and the one that was modified to adjust to the conditions in the greenhouse of Marín N.L. In order to accomplish this, the simulations of the corresponding models in Simulink of Matlab were made. The values of the parameters and entries are in Appendix A. The time of simulation was of 72 hours (3 days).

The validation of the model will be made comparing the real measurements inside the greenhouse against the simulations made with:

a) The model originally taken from base, developed by [Frank Tap F. [2000]], equations (1), (2), (3) and (4).
b) The modified model adjusted to the conditions of the greenhouse of Marín N.L., adding to the model of Tap the equations (6), (9), (10), (11), (13) and (14).

Simulations results

a) Comparison between the real measurements made inside the greenhouse and the original model taken from base.

The results of the simulation are presented in Figure 5.

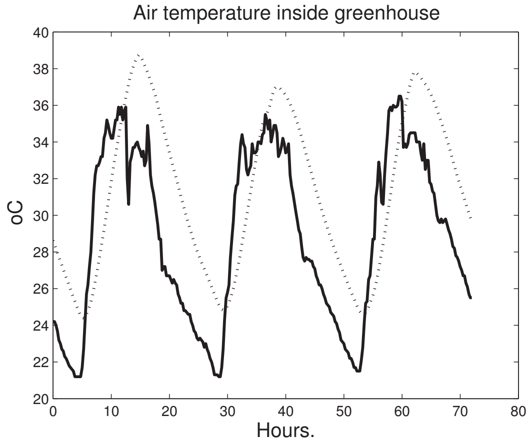

Fig. 5. Temperature comparison results.
Real measurements - Continuous line
Original model simulation - Dot line

The statistics of the difference between the simulation and the real measurements are in table 4.1.

Table 4.1
average =3.88
minimum =0.14
maximum =8.0
standard deviation =1.61

b) Comparison between the real measurements made inside the greenhouse and the modified model.

The results of the simulation are shown in Figure 6.

The statistics of the difference between the simulation and the real measurements are in table 4.2.

Table 4.2
average =1.21
minimum =0.00067
maximum =7.09
standard deviation =1.07

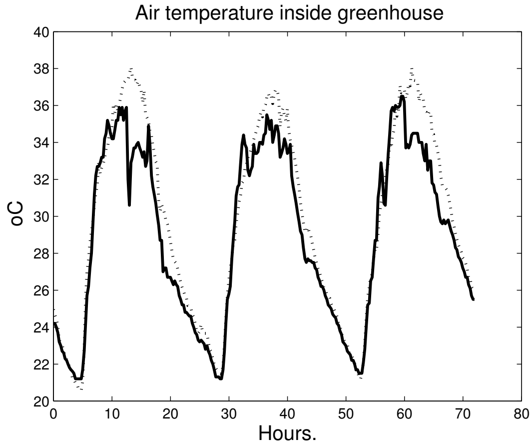

Fig. 6. Temperature comparison results.
Real measurements - Continuous line
Modified model simulation - Dot line

When comparing the behavior of the models original and modified by means of real measurements carried out inside the greenhouse of Marin N.L. when using simulations, it can be observed that the temperature obtained through the modified model at the conditions of the greenhouse of Marin N.L. better adjust to the real measurements taken in the inside (Figure 6), that the ones that were obtained with the original model taken from base (Figure 5). This also are reflected in the statistic of the differences between the results of the simulations and the measurements actually carried out in the inside, obtaining an average difference of 1.21C, maximum value of 7.09 and minimal of 0.00067 for the model modified and adjusted for the greenhouse of Marín; whereas for the model originally taken from base, the average of the difference was of 3.88C, maximum of 8.0 and minimum of 0.14.

7. CONCLUSIONS

In this paper, the modifications and necessary adjustments were carried out to obtain a dynamic model of climate that better adjusts to the conditions of a greenhouse in Marín N.L. México. In order to achieve this goal, the effects of the typical elements and equipments were added according to the climatic zone where the greenhouse is located. This locality corresponds to a climatic zone catalogued as extreme, requiring the use of elements that try to cooling the air inside the greenhouse. For this reason, the use of nebulizers is widely required, and is of supreme importance consider the effect of the additional humidity in the model.

The results of the validation (Figures 5 and 6, Tables 4.1 and 4.2) allow to conclude that the model obtained in this paper adjusts better to the conditions of the greenhouse of Maín N.L. and that is useful when it is required to simulate the climate inside a greenhouse where it is necessary to take into account the elements of shade cloths, forced ventilation, humidity added and variations of density of the air by consequence of changes in humidity.

8. ACKNOWLEDGMENTS

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Appendix A. STATES, INPUTS, FUNCTIONS AND PARAMETERS

Functions

Q	Humidity add for fogs $\frac{\mathrm{Kg}}{\mathrm{s}\cdot\mathrm{m}^2}$
D_g	Air vapor pressure deficit, kP_a
s	Saturated water vapor-pressure slope, $\frac{kPa}{°C}$
g	Leaf conductance
W_c^*	Humidity ratio at sat. cover vapor pressure
P_c^*	Saturated vapor pressure at cover
T_c	Cover temperature
W_g	Greenhouse air humidity ratio
P_g	Greenhouse air vapor pressure
λ	Vaporization energy of water, $\frac{Joules}{\mathrm{g}}$
K_v	Ventilation heat transfer coeff., $\frac{W}{°C\cdot\mathrm{m}^2}$
E	Crop transpiration rate, $\frac{\mathrm{g}}{\mathrm{s}\cdot\mathrm{m}^2}$
M_c	Condensation water flow, $\frac{g}{m^2 s}$
R	$\mathrm{CO_2}$ Crop respiration, $\frac{g}{\mathrm{s}\cdot\mathrm{m}^2}$
P	$\mathrm{CO_2}$ Crop photosynthesis, $\frac{g}{\mathrm{s}\cdot\mathrm{m}^2}$
ϕ_v	Ventilation flux, $\frac{\mathrm{m}}{\mathrm{s}}$
ϕ_{vent}	Ventilation flux for windows, $\frac{\mathrm{m}}{\mathrm{s}}$

Inputs

T_o	Outside air temperature, °C
T_p	Heating pipe temperature, °C
G	Short-wave radiation, watts$\cdot$m^{-2}
C_o	Outside air $\mathrm{CO_2}$ concentration, $\frac{g}{\mathrm{m}^3}$
V_o	Outside water vapor concent., $\frac{\mathrm{Kg}}{\mathrm{m}^3}$
W	Wind speed $\frac{\mathrm{m}}{\mathrm{s}}$
Q_f	Water consuming for fogs, $\frac{\mathrm{m}^3}{\mathrm{s}}$

System states

T_g	Greenhouse air temperature, °C
T_s	Greenhouse soil temperature, °C
C_i	Greenhouse CO$_2$ concent., $\frac{g}{\mathrm{m}^3}$
V_i	Greenhouse water vapor concent., $\frac{\mathrm{Kg}}{\mathrm{m}^3}$

Parameters

$\phi_{fan} = 11.4$	Ventilation flux for fans, $\frac{\mathrm{m}}{\mathrm{s}}$
$c_p = 1010$	Air specific heat, $\frac{Jouls}{Kg\cdot\ {}^\circ C}$
$C_s = 120000$	Greenhouse soil heat cap., $\frac{Jouls}{Kg\cdot\ {}^\circ C}$
$C_h = 2010$	Water vapor specific heat, $\frac{Jouls}{Kg\cdot\ {}^\circ C}$
$K_r = 0.3349$	Roof heat transfer, $\frac{W}{{}^\circ C\cdot\mathrm{m}^2}$
$K_s = 5.75$	Soil heat transfer, $\frac{W}{{}^\circ C\cdot\mathrm{m}^2}$
$\eta = 0.7$	Radiation conv. factor
$K_d = 2$	Soil to soil heat transfer, $\frac{W}{{}^\circ C\cdot\mathrm{m}^2}$
$\alpha = 0$	Pipe air heat transfer, $\frac{W}{{}^\circ C\cdot\mathrm{m}^2}$
$Z = 0.6$	Effective solar radiation
$T_d = 19$	Deep soil temperature, °C
$V_g = 4555.4$	Greenhouse volume, m^3
$A_g = 1050$	Greenhouse surface, m^2
$\varphi_{inj} = 0$	CO$_2$ Injection flux, $\frac{g}{\mathrm{s}\cdot\mathrm{m}^2}$
$r_w l = 100$	Rel. lee window opening
$r_w w = 100$	Rel. windward window opening
$W_L = 75$	Leaf dry weight, $\frac{g}{m^2}$
$LAI = 3$	Crop leaf area index
$W_m = 0.17$	Crop dry weight, $\frac{Kg\mathrm{CH_2O}}{m^2}$
$M_{air} = 1.29$	Dry air density at 0 ${}^\circ C$, $\frac{Kg}{m^3}$
$\gamma_o = 1.205$	Dry air density at 20 °C, $\frac{Kg}{m^3}$
$\rho = 998$	Specific mass of water, $\frac{Kg}{m^3}$
$P_{atm} = 101.0$	Atmospheric air pressure, kPa
$\omega = 0.622$	Humidity ratio
$q = 0.01$	Evaporation radiation, $\frac{m^2}{g}$
$r = 0.01$	Ev. vapor pressure deficit, $\frac{m^2}{g}$
$n = 0.098$	Parameter of radiation
$g_b = 10$	Boundary layer conductance, $\frac{mm}{s}$
$\gamma = 0.067$	apparent psychometric constant, $\frac{kPa}{{}^\circ C}$
$\epsilon = 3$	Inside outside cover heat resistance.
$s_1 = 0.00018407$	Sat. water vapor press. par. 1, $\frac{kPa}{{}^\circ C^3}$
$s_2 = 0.00097838$	Sat. water vapor press. par. 2, $\frac{kPa}{{}^\circ C^2}$
$s_3 = 0.051492$	Sat. water vapor press. par. 3, $\frac{kPa}{{}^\circ C}$
$\Lambda = 0.46152$	Pressure constant, $\frac{N\ m}{{}^\circ C\ g}$
$a_1 = 0.611$	Saturation vapor pressure, kPa
$a_2 = 17.27$	Saturation vapor pressure
$a_3 = 239$	Saturation vapor pressure, °C
$\zeta = 0.000027060$	Renewal rate parameter, $\frac{m}{s}$
$\sigma = 0.000071708$	Renewal rate parameter
$\chi = 0.0156$	Renewal rate parameter
$\xi = 0.000063233$	Renewal rate parameter
$\psi = 0.000074$	Renewal rate parameter
$L1 = 2501$	Vaporization energy coefficient, $\frac{J}{g}$
$L2 = 2.381$	Vaporization energy coefficient, $\frac{J}{g\ {}^\circ C}$
$g_1 = 20.3$	Leaf conductance, $\frac{mm}{s}$
$g_2 = 0.44$	Leaf conductance
$g_3 = 0.0025$	Leaf conductance, $\frac{s\ m^2}{\mu mol}$
$g_4 = 0.00031$	Leaf conductance, $\frac{m^3}{g}$
$m_1 = 0.0010183$	Mass transfer, $\frac{g}{s\ m^2}$
$m_2 = 0.33$	Mass transfer
$M_{CO_2} = 0.044$	Carbon dioxide molar mass, $\frac{Kg}{mol}$
$M_{CH_2O} = 0.03$	Glucide unit molar mass, $\frac{Kg}{mol}$
$Q^{10} = 1.40$	Respiration of the crop
$\rho_r = 1.2 \times 10^{-7}$	Maintenance respiration, $\frac{Kg\mathrm{CH_20}}{Kg\cdot s}$
$\tau_c = 0.0029$	Leaf CO$_2$ efficiency, $\frac{m}{s}$
$T_{eff} = 0.54$	Amplitude of temp effect, $\frac{1}{{}^\circ C}$
$K_p = 0.58$	Crop light extinction coefficient
$T_{min} = 7$	Min. temp for photosynthesis, ${}^\circ C$
$T_{max} = 38.5$	Max. temp for photosynthesis, ${}^\circ C$
$T_{cs} = 19840$	Smoothness for temp effect, ${}^\circ C^2$
$\in_p = 2.46\times10^{-9}$	Quantum yield efficiency, $\frac{Kg\mathrm{CO_2}}{\mu mol}$
$m = 0.10$	Leaf transmission factor
$Q_f = 0.0011$	Fog water consumption $\frac{m^3}{s}$

Appendix B. ALGEBRAIC EQUATIONS

$$E = W_L \frac{qS_n\eta G + r\rho c_p D_g g_b}{\lambda(S + \gamma(1 + \frac{g_b}{g})} \tag{B.1}$$

$$\begin{aligned}
D_g &= a_1 e^{\frac{a_2 T_g}{a_3 + T_g}} - \Lambda(T_g + T_o)V_i \\
s &= s_1 T_g^2 + s_2 T_g + s_3 \\
g &= g_1(1 - g_2 e^{-g_3 G})e^{-g_4 C_i} \\
\lambda &= L1 - L2T_g
\end{aligned}$$

$$K_v = M_{Air} \cdot c_p \cdot \phi_v \tag{B.2}$$

$$C_g = M_{Air} \cdot c_p \cdot \frac{V_g}{A_g} \tag{B.3}$$

$$\phi_{vent} = (\frac{\sigma r_{wl}}{1 + \chi r_{wl}} + \zeta + \xi r_{ww})W + \psi \tag{B.4}$$

$$M_c = \begin{cases} m_1 \left|T_g - T_c\right|^{m_2} (Wg - W_c^*) & W_g > W_c^* \\ 0 & W_g \leq W_c^* \end{cases}$$

$$\begin{aligned}
W_c^* &= \frac{\omega P_c^*}{P_{atm} - P_c^*} \\
P_c^* &= a_1 e^{\frac{a_2 T_c}{a_3 + T_c}} \\
T_c &= \frac{\epsilon}{\epsilon + 1} T_o + \frac{1}{\epsilon} T_g \\
W_g &= \frac{\omega P_g}{P_{atm} - P_g} \\
P_g &= \Lambda(T_g + T_o)V_i
\end{aligned}$$