POSTER PRESENTATION

´InverSim´: A Simulation Model for Greenhouse

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Abstract

The central region of Argentina is characterized by a temperate climate with a sudden increase of maximum temperature after winter that brings outstanding problems in the yield and quality of most of the greenhouse crops during the warm season. The forecast of the greenhouse climate is essential to improve the design of these structures and the environmental handling. *´InverSim´* is a mathematical model that simulates an hourly evolution of the air temperature and the humidity inside the greenhouse during the course of a day. Balance equations of heat and water steam have been used for the construction of the model. These have allowed us to establish a single system of two equations with two unknown terms, thus allowing us to estimate the temperature and the relative humidity with some time frequency. For the greenhouse ventilation we have only taken into consideration the dynamic effect of the wind and the stack effect induced by buoyancy forces. The model incorporates the fogging system and calculates the amount of water required to maintain the air temperature below and optional threshold. The transpiration of the crop has also been taken into account. For the validation of this model a metal greenhouse, 9 m wide, 24 m long and 6 m high with lateral and roof ventilation has been used for the collection of data over a 12-day period. The measurement of outside conditions in the direct vicinity of the greenhouse has been used as input for the model. In the inside of the greenhouse we have placed one weather station with seven temperature and relative humidity sensors, with values being stored every hour. The results show that the predicted and observed temperature and relative humidity have been satisfactory, with a correlation coefficient over 0.88 for temperature and over 0.70 for relative humidity. The root mean square error (RMSE) used to test the average differences between the predicted and the observed value is between 3.9 and 11.8. The results achieved with the model are discussed and their applicability addressed.

INTRODUCTION

The use of greenhouses facilitates the production of crop when weather conditions hinder it, therefore enabling the growth of quality and productivity (Seginer et al., 1994). Particularly in summer, one of the main aims is to achieve an efficient weather control (Boulard and Baille, 1993). The Argentine central region stands out for a tempered weather which causes considerable yield and quality problems for most of the crop in greenhouses during the warm season. In that case, the weather forecast for greenhouses is essential to improve the design of structures, the treatment of the environment and an efficient control programme (van Henten and Bontsema, 1996). Cooling through natural ventilation is one of the most important and cheapest alternatives for most greenhouses placed in mediterranean climates due to the harmful effect of the high temperatures on the physiology of the different crops and to obtain a high quality product (Hanan, 1997). The ventilation allows the exchange of energy and mass to take place (Kittas et al., 2003) regarding the greenhouse as a solar collector and its behaviour being modelled through the use of a single-energy balance equation (Boulard and Baille, 1993). The aim of this work was to develop a mathematical simulation model to describe the dynamic behaviour of air temperature and humidity inside the greenhouse.

MATERIALS AND METHODS

Theory

The greenhouse thermal behaviour during day time is described through the use of a simplified energy balance equation (Boulard and Baille, 1993; Bot, 1983; Takakura, 1989; Tantau, 1989; Boaventura Cunha et al., 1997).

$$\tau S - Ks\,\Delta T - Kl\,\Delta e - Kc\,\Delta T = 0 \qquad (\mathrm{W\ m^{-2}}) \tag{1}$$

The first three terms represent the greenhouse radiative gain and the sensible and latent heat exchange by ventilation (Boullard and Baille, 1993). Ks and Kl are proportional to the air exchange rate of the greenhouse. The fourth term represents the overall sensible heat transfer at the cover surface and includes the convective and radiative (thermal) losses (Baille et al., 1983).

Ks is calculated with the help of the following expression:

$$Ks = \frac{\rho\, Cp\, Vg\, N}{3600\, Sg} \qquad (\mathrm{W\ m^{-2}\ K^{-1}}) \tag{2}$$

where N is an air exchange rate (Boulard and Baille, 1993):

$$N = (\,\zeta\,(\tfrac{So}{2})\,C^{0,5}\,v\,)(\frac{3600\,Sg}{Vg}) \qquad (\mathrm{h^{-1}}) \tag{3}$$

The previous equation only shows the dynamic effect. The “chimney” effect due to thermal buoyancy forces is considered insignificant when wind velocity is over 1 m s^{-1} and gains relative importance when the wind velocity tends to nil (Boulard et al., 1991). In order to simplify calculations, when wind velocity is under 1 m s^{-1} it is considered the same as 1 m s^{-1}. In this way the ventilation effect due to buoyancy forces is disregarded (Bouchet et al., 2005).

The Kl parameter is calculated through the following formula (Boulard and Baille, 1993):

$$Kl = \frac{Fc\ \rho\,\lambda\ Vg\ N}{3600\ \ Sg} \qquad (\mathrm{W\ m^{-2}\ Pa^{-1}}) \tag{4}$$

The Kc parameter is calculated through the following formula (Boullard and Baille, 1993):

$$Kc = A + B\,v \qquad (\mathrm{W\ m^{-2}\ °K^{-1}}) \tag{5}$$

The variation in the content of air water vapour is assessed through a balance, where the soil evaporation and the condensation in the inside of the cover greenhouse are not taken into account. The water vapour balance is calculated with the following formula, modified according to Jolliet (1994):

$$a\ \alpha\,\tau\,S + b\,\delta_{(Te)}\,\Delta T - (b + Kl)\,\Delta e + b\,D_{(e)} + \lambda W = 0 \qquad (\mathrm{W\ m^{-2}}) \tag{6}$$

Parameters *a* and *b* have been calculated for a tomato crop (Jolliet, 1994). Parameter *a* depends upon the leaf area index of the crop reflecting the incidence of radiation on crop transpiration. Parameter *b* depends upon leaf area index and on incident solar radiation on crop. This parameter enables us to estimate the incidence of vapour pressure deficit over energy loss due to crop transpiration:

$$\lambda\, Et = a\, S + b\, D_{(i)} \quad \text{(W m}^{-2}\text{)} \qquad (7)$$

$$\delta_{(Te)} = 1.41\ 10^{10}\ (\frac{3928.5}{(T_e - 41.5)^2})\ exp(\frac{-3928.5}{T_e - 41.5})$$

$$es_{(e)} = 611.0\, exp\left(\frac{17.27\, T_{(e)}}{243.5 + T_{(e)}}\right) \qquad e_{(e)} = \frac{HR_e}{100} es_{(e)} \quad \text{(Pa) (Iribarne and Godson, 1981)}$$

The values in *a* and *b* arise from the transpiration of a tomato crop and it was obtained by Jolliet (1994) who followed a non-linear regression analysis:

$$a = 0.154\ Ln\,(1 + 1.1\ LAI^{1.13}) \quad \text{(adim)} \qquad (8)$$

$$b = \frac{1.65\ LAI\ (\ 1 - 0.56\ exp(\frac{-\tau\, S}{13})}{\gamma} \quad \text{(W m}^{-2}\text{ Pa}^{-1}\text{)} \qquad (9)$$

Combining equations 1, 6 and 7 we obtain a two-equation system with two unknown, which allow us to estimate the gradients between the inside and the outside of the greenhouse, water steam (Δe) and temperature (ΔT).

$$\Delta T = \frac{(\frac{b + Kl}{Kl})\, \tau\, S - b\, D_{(e)} - a\, \alpha\, \tau\, S - W}{b\, \delta_{(Te)} + (\frac{(b + Kl)(Ks + Kc)}{Kl})} \qquad (10)$$

$$\Delta e = \frac{\tau\, S - \Delta T\, (Ks + Kc)}{Kl} \qquad (11)$$

The mathematical model has been translated into VBasic language for Windows® for this to be used through personal computers.

Experimental Arrangement

To validate the model a metal greenhouse has been used (ADC Greenhouses®) in Santa Fe, Argentine (31° 30' S, 62° 15' W). The dimensions of the greenhouse were 9 m wide, 24 m long and 6 m high, with lateral and roof vent. The longitudinal orientation of the greenhouses was E-W, with roof vents on north side from gutter. Seven (7) sensors were placed inside the greenhouse in order to measure temperature (°C and relative humidity (%), through a weather automatic station LiCor LI-1400 (Lincoln, USA). Outside the greenhouse, a weather automatic station Davis Weather-Link® (Hayward, USA) was installed containing sensors to measure outdoor conditions: air temperature (°C), relative humidity (°C), solar radiation (W m-2) and wind velocity (m s-1). All readings have been carried out every hour and the sensors placed 2.0 m above the floor. Outside meteorological information was entered into the ´InverSim´ model in order to predict the course of inside temperature and relative humidity in the greenhouse. Measurements were developed over a 12-day period, using for the comparison only the values corresponding to the first week. The model performance can be evaluated by the Root Mean Square Error (RMSE) (Pielke, 1984), regression lines and determination coefficient (R2) between measurements and calculated dates. Papaya (*Carica papaya* L.)

plants were grown in the greenhouse at a leaf area index of the 1.1 determined by non-destructive measurements (length x width of the leaves) on a random sample of 5 plants. The method was calibrated using a planimeter.

RESULTS AND DISCUSSION

Figure 1 shows the course of the changes in calculated and measurement temperature in the greenhouse during 1 week. In the first day a positive difference (calculated values > observed values) was recorded during the hours the greenhouse was closed (Figure 1), which would imply an overestimation of the greenhouse effect. It is very likely that the solar radiation transmittance coefficient (Bouzo and Pilatti, 1999) was overestimated for the conditions of this experiment. During the second day the agreement between observed and predicted temperatures was very good, except during the hours near noon, where differences turned positive. This shall imply an accurate assessment of sensible and latent heat loss due to hourly restoration (Boulard and Baille, 1993) taking into account that during this day the ventilation period was higher than on the first. In the third day ventilation was carried out with lateral and roof vents. Overestimation of temperature calculated during the morning, before starting the ventilation, was similar to one predicted for one day . However, high sensitivity in the model was observed in face of changes in the hourly intensity of solar radiation during the diurnal period shown through temperature fluctuations (Figure 1). During the ventilation period the average rate of the external velocity was 2.2 m s^{-1}, and it was never under 1.3 m s^{-1}. This fact might have allowed a simulation of good behaviour in the roof ventilation being wind velocity over 1 m s^{-1} (Boulard et al., 1991). The highest temperature values predicted during the ventilation period might have been due to the fact that wind direction was from quadrant N, having a windward influence as regards roof windows which might have caused a decrease in the hourly restoration of inside air (Anton and Montero, 1992). In the fourth day, the overestimation of temperature during the beginning of the morning might have been due to a very low wind velocity (< 0.3 m s^{-1}) being the aerodynamic coefficient used probably bound to examination (Bouchet et al., 2003). In the opposite direction, we can observe an underestimation of the temperature predicted from 4:00 PM, when the wind velocity was over 4 m s^{-1}. Since the windows were closed at 5:00 PM, this could mean an overestimation of coefficients used to predict the heat transference whole coefficient (Bailey and Cotton, 1980; Baille et al., 1983; Boulard and Baille, 1993). On the fifth day, the greenhouse remained closed due to the fact that outside maximum temperature was low (< 15 °C) an acceptable behaviour of the calculated temperatures was observed. In the sixth day an underestimation of temperature is observed between 4:00 PM and 7:00 PM and in the seventh day the calculated temperatures reveal a similar behaviour to the one observed for previous days (Figure 1). The temperatures higher than the ones recorded during diurnal time being the greenhouse closed and low temperatures after the windows were opened (Figure 1). In general, there was good agreement between the observed and calculated temperatures, which reveals an acceptable behaviour of the model for the experimental conditions used.

The regression line obtained after 168 observations between observed and calculated temperature confirm the visual analysis carried out (Figure 2), considering that the determination coefficient (R^2) was 0.88 and the RMSE was 3.9. Also, the value of the regression equation slope had a very near to one (0.99) (Figure 2). This indicate a very similar course between the observed and the calculated values. However, for the normal values of measured hourly relative humidity a smaller agreement with the ones calculated by the model was observed (R^2 = 0.70) (Figure 3). The lineal equation slope (0.80) an underestimation of the relative humidity calculated by the model. is inferred. In Tables 1 and 2 the statistical analysis for the validation period of the greenhouse inside temperature and relative humidity can be respectively observed. In this case, the days studied are considered separating between diurnal and nocturnal periods. It is seen that the determination coefficients (R^2) are lower than the ones shown in Figures 2 and 3 due to the decrease in the amount of data used, and as a result of the existing compensation when they are considered as a whole. In Table 1 we can objectively see the comments for Figure 1. It can be seen that the differences between observed and calculated values are never over 3 °C, which reveals a very good performance of the *´InverSim´* model (Table 1), with a better agreement between observed and predicted temperatures for the night period. Regarding the relative humidity, absolute differences between observed and predicted values some times exceeded 15 %, having a similar behaviour been detected between observed and predicted values for day and night periods (Table 2).

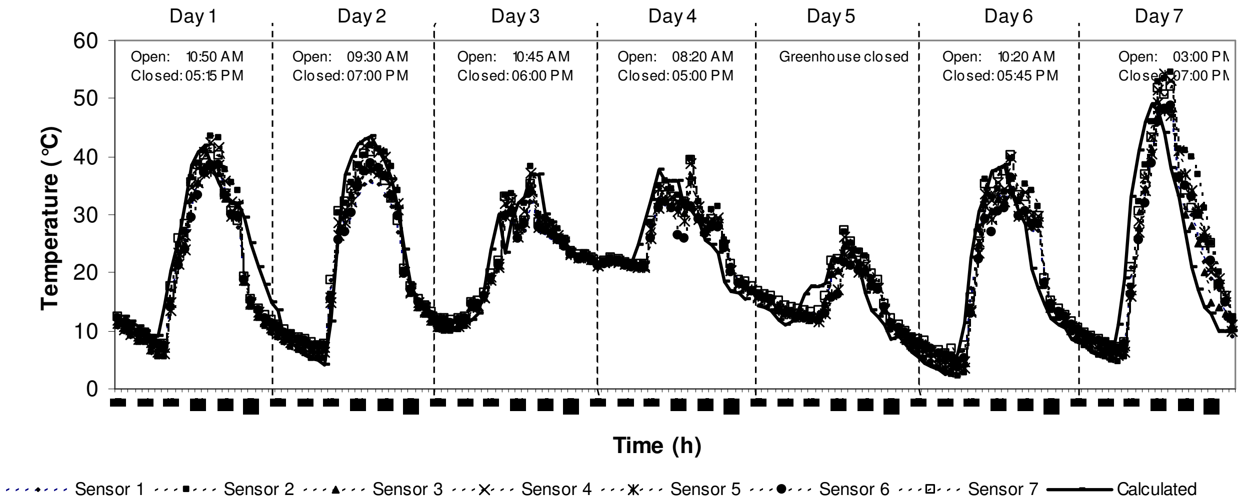
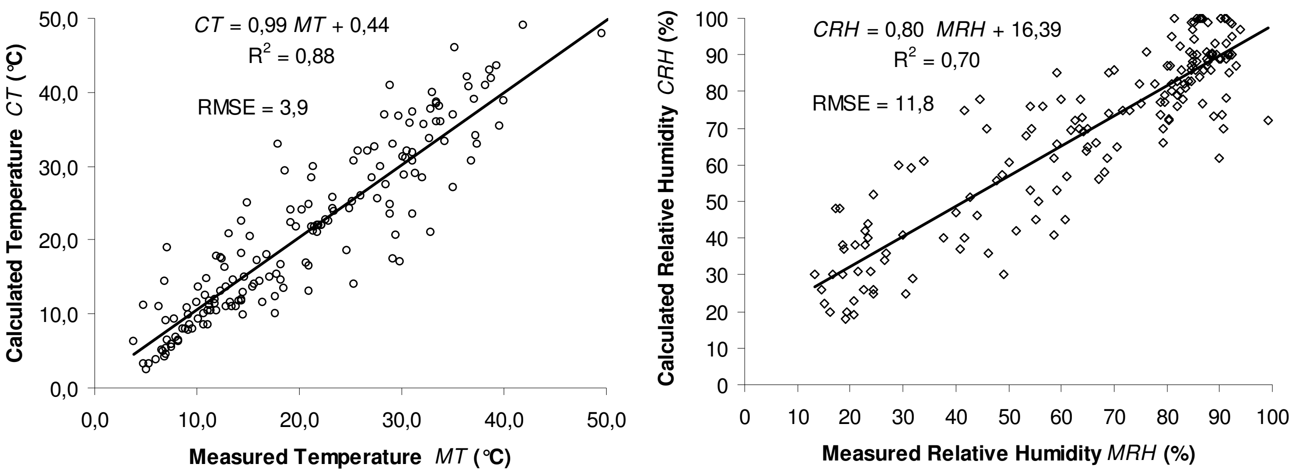


Figure 1. Comparison of changes between temperatures inside the greenhouse calculated by the *´InverSim´* model and temperatures measured with the seven sensors.



(a) (b)

Figure 2: Calculated vs measured values in the air inside the greenhouse for: a) temperature (°C) and b) relative humidity (%).

Table 1: Statistical analysis for the validation of the model. Comparison between air temperature calculated and measured values inside the greenhouse for each day according to night (N) and day periods (D). R^2 stands for resolution coefficient and S for standard diversion for temperature hourly differences values.

		Mean Values		Difference			S
Day	Period	Meas.	Calc.	Abs. (°C)	Rel. (%)	R^2	hourly
1	N	9,1	11,2	2,1	23,1	0,86	1,34
	D	31,7	33,7	2,0	6,3	0,83	1,64
2	N	10,3	12,7	2,4	23,3	0,97	2,83
	D	32,9	35,6	2,7	8,2	0,92	1,91
3	N	13,8	14,0	0,2	1,4	0,89	0,75
	D	27,6	30,0	2,4	8,7	0,45	2,52
4	N	22,2	23,1	0,9	4,1	0,33	1,38
	D	30,9	31,1	0,2	0,6	0,26	1,47
5	N	16,3	14,5	-1,8	11,0	0,60	0,96
	D	18,7	19,0	0,3	1,6	0,30	1,67
6	N	7,4	6,4	-1,0	13,5	0,78	0,73
	D	30,0	30,2	0,2	0,7	0,30	2,52
7	N	10,0	9,7	-0,3	3,0	0,69	1,80
	D	37,2	36,1	-1,1	3,0	0,26	3,50

Table 2: Statistical analysis for the validation model. Comparison between air relative humidity predicted and observed values inside the greenhouse for each day according to night (N) and day periods (D). R^2, determination coefficient and S, standard deviation of relative humidity hourly differences values.

		Mean Values		Difference			
Day	Period	Meas.	Calc.	Abs. (% RH)	Rel. (%)	R^2	S
1	N	91,2	75,8	-15,4	16,9	0,67	4,51
	D	32,8	29,4	-3,4	10,4	0,65	5,27
2	N	85,6	85,6	0,0	0,0	0,84	2,92
	D	27,1	42,8	15,7	57,9	0,72	7,68
3	N	79,7	79,8	0,1	0,1	0,52	3,12
	D	56,0	58,3	2,3	4,1	0,30	6,46
4	N	86,1	85,0	-1,1	1,3	0,88	3,67
	D	60,9	63,9	3,0	4,9	0,23	5,74
5	N	84,4	89,8	5,4	6,4	0,68	3,33
	D	63,8	66,9	3,1	4,9	0,49	4,48
6	N	87,2	88,0	0,8	0,9	0,33	5,17
	D	28,5	42,6	14,1	49,5	0,50	7,94
7	N	82,2	86,5	4,3	5,2	0,54	5,55

Notation

A = 6 for single and 4 for double cover greenhouse, respectively.

a = Parameter which characterizes the influence of solar global over transpiration, adim..

B = 0.5 for single and 0.2 for double cover greenhouse, respectively (Bailey and Cotton, 1980; Baille et al., 1983).

b = parameter which characterizes the influence of saturation deficit over transpiration, W m^{-2} Pa^{-1}.

C = wind coefficient, adim.

Cp = air thermal capacity, J Kg^{-1} K^{-1}.

D(e) = Deficit pressure vapour outside of the greenhouse, Pa.

$D_{(i)}$ = Air vapour pressure deficit inside the greenhouse, Pa.

Fc = conversion factor between the air water vapour content (kgw kga^{-1}) and the air water vapour pressure, Pa. (= 6.25 x 10^{-6} kgw kga^{-1} Pa^{-1})

Kc = Overall heat transfer coefficient of the cover material, W m^{-2} K^{-1}.

Kl = Coefficient of ventilation heat exchange for latent heat, W m^{-2} Pa^{-1}.

Ks = Coefficient of ventilation heat exchange for sensible heat, W m^{-2} K^{-1}.

LAI = Leaf area index, m^2 m^{-2}.

N = Air exchange rate, h^{-1}.

S = Outside global radiation, W m^{-2}.

Sg = Greenhouse ground surface, m^2.

So = Surface of vent openings, m^2 m^{-2} ground.

v = Wind velocity, m s^{-1}.

v = Wind velocity, m s^{-1}.

Vg = Greenhouse volume, m^3.

ζ = Aerodynamic coefficient, adim. (Bouchet et al., 2003).

ρ = Air density, kg m^{-3}.

λ = Latent heat of water vaporization (= 2500 KJ kg^{-1} K^{-1}).

τ = Global radiation transmittance; 0.65 for single-cover and 0.6 for double-cover (Bouzo and Pilatti, 1999).

γ = Psicrometric constant (= 66 Pa K^{-1})

$\propto$ = Coefficient of crop solar absorption (= 0.95)

δ(Ti) = Slope of gradient saturation curve at temperature inside greenhouse, Pa °K^{-1}.

Δe = Difference between the inside and outside water vapour pressure, Pa.

τS = Incident solar global on crop, W m^{-2}.

ΔT = Difference between the inside and outside air temperature, K.

λW = Energy dissipated due to the evaporation of the fraction of water added through nebulization, W m^{-2}.

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