ACCURACY COMPARISON OF A MECHANISTIC METHOD AND COMPUTATIONAL FLUID DYNAMICS (CFD) FOR GREENHOUSE INNER TEMPERATURE PREDICTIONS

E. Rico-García[1¶]; R. Castañeda-Miranda[2];
J. J. García-Escalante[3]; A. Lara-Herrera[4];
G. Herrera-Ruiz[5]
[1,2,3,5]Laboratorio de Biotrónica. Universidad Autónoma de Querétaro.
Cerro de las Campanas s/n, Col. Las Campanas.
Querétaro, Querétaro, MÉXICO.
Correo-e: ricog@uaq.mx. (¶Autor responsable).
[4]Unidad de Agronomía. Universidad Autónoma de Zacatecas.
Jardín Juárez Núm. 147, Centro Histórico,
Zacatecas, Zacatecas. MÉXICO.

ABSTRACT

Air movement originated by ventilation in greenhouses is an important factor that affects the uniformity of their climatic conditions and consequently the uniformity of plant growth and quality. A prediction of the greenhouse climatic conditions is really important to take the appropriate actions to control the inner climate. In this work a mechanistic model and a CFD model have been compared to determine the accuracy of both models in predicting the inner temperature in greenhouses under Mexican climate conditions. The results show that the mechanistic model ($R^2 = 0.97$) has a best fit of the inner temperature than the CFD model ($R^2 = 0.94$). However both models can be used for greenhouse engineering tool design.

ADDITIONAL KEY WORDS: natural ventilation; computational fluid dynamics, climatic model, energy balance.

COMPARACIÓN DE LA PRECISIÓN DE LAS PREDICCIONES DE LAS TEMPERATURAS INTERNAS DE INVERNADEROS CON MÉTODOS MECANISISTAS Y DE DINÁMICA DE FLUIDOS COMPUTARIZADOS

RESUMEN

El movimiento de aire causado por la ventilación en los invernaderos es un factor importante que afecta la uniformidad de sus condiciones climáticas y consecuentemente la uniformidad y calidad del crecimiento de las plantas. La predicción de las condiciones climáticas de los invernaderos es realmente importante para tomar las acciones apropiadas para controlar el clima interno. En este trabajo se compararon un modelo mecanicista y otro basado en la dinámica de fluidos computarizada para determinar su precisión para predecir las temperaturas internas de los invernaderos en las condiciones climáticas mexicanas. Los resultados muestran que el modelo mecanicista tiene un mejor ajuste a las temperaturas internas ($R^2 = 0.97$) que el basado en la dinámica de fluidos computarizada ($R^2 = 0.94$). Sin embargo, ambos modelos pueden ser usados como herramientas ingenieriles para el diseño de invernaderos.

ADDITIONAL KEY WORDS: natural ventilation; computational fluid dynamics, climatic model, energy balance.

Recibido: 10 de enero, 2006
Aceptado:27 de junio, 2007

Revista Chapingo Serie Horticultura 13(2): 207-212, 2007.

INTRODUCTION

Forced ventilation systems are not common in greenhouses. Therefore, natural ventilation is the main method used in greenhouses to control the indoor climate. Also it is cheaper than forced ventilation because it does not need as much maintenance as forced ventilation. However, natural ventilations systems offer a limited control over the air flow through the greenhouse causing difficulties in controlling the indoor climatic conditions. Hence, computer modelling of greenhouse ventilation has been applied to the climatic conditions inside the greenhouse.

On the other hand, the climatic models based on physical properties let us foreknow the behaviour of the different elements that make the greenhouse system and their relationship with each other within the greenhouse. In this sense the focus of most research is to develop models that take into account the knowledge in a quantitative manner and are employed to design engineering tools applied to greenhouses. These tools are employed in the greenhouse design and for the analysis and implementation of new algorithms and control methods (Bakker *et al*., 1995). In countries where the greenhouse technique is still new, there is the necessity to develop models according to the climatic conditions of the region. This is the case of Mexico.

In the literature there are some models reported, the black box is a good example, this model is based on the input and output data of the process which is been simulated (Udink-Ten-Cate, 1983; Cunba *et al*., 1992). However, these kinds of models do not take into account any direct knowledge of the physical system. Hence, they are not suitable to be used in any greenhouse configuration.

Other models are based on the physics laws, where the processes responsible for the energy and mass transfer are to be analysed. These kind of models can describe in detail the climatic conditions within the greenhouse in relation to the outside climatic conditions. It can be included the physical properties of the greenhouse and its facilities (Bot, 1983).

The mechanistic model developed in this work describes the behaviour of the most important variables in the inner climate of a greenhouse: air, soil, and cover temperatures and the total humidity (Jones *et al*., 1995; Tap, 2000; Tavares *et al.*, 2001; Van-Henten, 2003) This model only takes into account the vertical flows and it is supposed that the horizontal variability do not exist.

As better computers have been developed the use of Computational Fluid Dynamics (CFD) has increased in the study of natural ventilation in greenhouses. Mistriotis *et al*. (1997) compared numerical results with experimental data obtained for various window configurations, at no-wind and low-wind speed conditions. They reported good agreement between the numerical and experimental data.

Boulard *et al*. (2002) used the CFD technique in the study of the distributed climate of greenhouses. They determined that CFD could lead to a better greenhouse design. Bartzanas *et al*. (2002) used this approach to investigate how the screen influences airflow and temperature patterns inside the greenhouse. Campen and Bot (2003) studied the ventilation of a Spanish 'parral' greenhouse by means of three-dimensional CFD. They also took into account the geometry of the surrounding area. The numerical results resembled experimental data obtained from tracer gas measurements within 15 %. Lately the use of CFD as technique for predicting and studying the climatic conditions in full-scale greenhouses has been increasing (Fatnassi *et al*., 2003; Molina-Aiz *et al*., 2004; Rico *et al*., 2006; Ould Khaoua *et al*., 2006).

The goal of this work is to make a quantitative comparison to determine the accuracy of mechanistic and CFD estimations in predicting the inner temperature in greenhouses under Mexican climate condition.

MATERIALS AND METHODS

In order to determine the ability of predicting the inner temperature in the greenhouse we compared results obtained from a mechanistic method and the results obtained from two-dimensional CFD simulations. Both models were calibrated against real data obtained in a full scale greenhouse.

Greenhouse description

The experimental greenhouse is located at the Queretaro University campus whose coordinates are: longitude, 100º 24' W; latitude, 20º 36' N; altitude, 1,820 m. The covered area is 964.8 m^2 (26.8 m wide and 36 m long). The greenhouse is 4.5 m high with the gutter at 3 m. The ridge is oriented north-south. It has four roof windows, one on each span, (0.9 m wide and 28 m long) and four side windows. The north and south windows are 2.5 m wide and 20 m long, the east and west windows are 2.5 m wide and 28 m long. All the windows are of the roll-up type. The roof and side ventilation areas are 10 and 24 % of the covered ground area, respectively (Figure 1).

Mechanistic model

The set of mathematical equations that describes the inner temperature as a function of the external climate con-

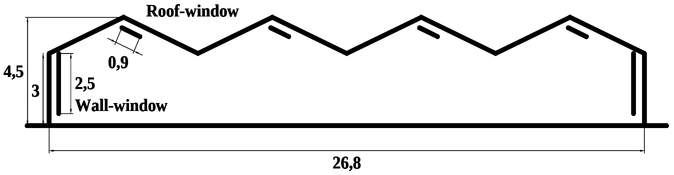

FIGURE 1. Greenhouse geometry. All dimensions are in meters.

ditions is shown in equations 1 and 2. For this model only the vertical flows are considered, assuming that the greenhouse does not have horizontal variability. The energy balance describing the inner air temperature T_i is given by:

$$C\frac{dT_1}{dt} = \eta G + \alpha_{ci}\left[A_r\left(T_r - T_i\right) + 2I_{LA}\left(T_c - T_i\right) + \left(T_g - T_i\right)\right] - \phi_v \rho_a C_p\left(T_i - T_o\right) + q_h$$

. . . . (1)

where C is the greenhouse heat capacity expressed in J·K^{-1}·m^{-2}; η is the radiation conversion factor; G is the outside short-wave radiation in W·m^{-2}; is the convection heat transfer coefficient in W·m^{-2}; A_r is the roof to soil rate; T_r is the roof temperature in ºK; T_i is the greenhouse inner temperature expressed in ºK; I_{LA} is the leaf area index; T_c is the crop temperature in ºK; T_g is the ground temperature in ºK; is the ventilation rate in m^3·s^{-1}; is the air density in kg·m^{-3}; C_p is the air specific heat in J·K^{-1}·kg^{-1}; q_h is the heat input in W·m^{-2}.

To improve the accuracy of the inner temperature description, the condensation and transpiration energy influences are needed. The energy balance for the inner absolute humidity x_i is shown in Equation .

$$V_l\rho_a\frac{dx_1}{dt} = \frac{1}{\lambda}\left(\frac{2I_{LA}\rho_a C_p}{\gamma\left(r_s + r_a\right)}\left[\delta^*\left(T_c - T_i\right) + \left(e_i^* - e_i\right)\right] + \alpha_{ci}\frac{\lambda}{C_p}\left(x_g^* - x_i\right)\right) - \frac{\phi_v}{A_g}\rho_a\left(x_i - x_o\right)$$

$$\frac{\partial\varphi}{\partial t} + \nabla\cdot\varphi\vec{V} = \nabla\cdot\left(\Gamma_\varphi\nabla\varphi\right) + S\varphi$$

$$\left(2.502x10^{-3}T^{3/2}\right)/\left(T + 194.44\right)$$

. . . .(2)

where V_l is the greenhouse volume air to soil area rate expressed in m^3·m^{-2}; x_i is the internal absolute humidity in kg·m^{-3}; λ is the water vaporization energy; is the thermodynamic constant in PaºK; r_s is the stomatic resistance in s·m^{-1}; r_a is the aerodynamic resistance in s·m^{-1}; is the leaf slope in PaºK; e_i is the internal mean vapour pressure in Pa; x_g is the soil absolute humidity in kg·m^{-3}; A_g is the covered ground surface in m; x_o is the external absolute humidity in kg·m^{-3}; and t is the time in s. The superscript * indicates that considered quantity is at saturated vapour pressure.

The result of the model simulation for air temperature was compared against climatic measurements inside the greenhouse. With this data, statistic parameters were obtained, which were taken as a base to determine the model performance. Model calibration and validation were made following the methodology described by Van-Henten (2003). In order to obtain model ability to describe the climate, the model was validated by simulations.

CFD model

The CFD method allows the explicit calculation of the airflow pattern by numerically solving the corresponding transport equations. The conservation equations describing these transport phenomena are of the general form Eqn :

. . . .(3)

where: $\vec{V}$ is the velocity vector; is the diffusion coefficient and is the source term. The symbol φ represents the concentration of the transported quantity, *i.e.* the air density in the mass conservation equation and in the momentum equations.

The software used to simulate the physics of the air flow was ANSYS/FLOTRAN v8.1. It is a software program based on the finite element method which numerically solves the above equation. To calibrate the computer model the numerical data were compared against measured data taken in full scale greenhouses. Table 1 summarises the air properties for simulations.

TABLE 1. Air properties used in the simulations. The values for thermal conductivity, viscosity and density varied according to the outside temperature.

Physic quantity	Unit	Model	Value
Specific heat	(J·kg^{-1}·K^{-1})		1,004
Thermal conductivity	(W·m^{-1}·K^{-1})		
Viscosity	(kg·m^{-1}·s^{-1})	$\mu = \left(1.4592x10^{-6}T^{3/2}\right)/\left(T + 110.56\right)$	
Density	(kg·m^{-3})	$\rho = P/\left(287.05T\right)$	
Atmospheric pressure	(Pa)	1,800 m^Z	81,388

^{Z}Height over the sea level.

Instrumentation set up

Internal air temperatures were read by means of LM335 precision temperature sensor (National Semiconductor) whose range of operation is -40 ºC to 100 ºC with accuracy of ± 1 ºC. It has an output voltage temperature coefficient of +10 MV $ºC^{-1}$ and a thermal response to 100 % of the final value, of four minutes in air. The sensors were protected with a passive solar shield. All sensors were calibrated in a room at a constant temperature of 25 ºC. Two capacitive sensors were used for humidity measurements (%) from Global Water Instrumentation Inc. These sensors were located at 2.20 m of height inside the greenhouse. For the temperature measurements in the cladding material and soil it was used RTD's from Omega Engineering Inc. The outside weather conditions: wind speed, the wind direction, solar radiation and humidity were recorded by means of a wheatear station, as part of TUNA® SCCII v5.0 developed at Queretaro State University. It was configured so it logged the data every five minutes.

The measurements of inside air velocity were read with a hot-wire anemometer whose range of operation is 0 $m{\cdot}s^{-1}$ to 20 $m{\cdot}s^{-1}$ with accuracy of ± 0.03 $m{\cdot}s^{-1}$ and recorded by means of digital multifunctional TESTO® 445 with a resolution of 0.01 $m{\cdot}s^{-1}$.

This data was used for determining boundary conditions for CFD computations, and as input data for the mechanistic model as well as for validation of both models.

Measures of accuracy

The coefficient of determination R^2 is one of the most used accuracy measurements to establish the reliability of predictions. Other measurements could be used for improving the confidence of estimated values. These are the percent standard error of the prediction (% SEP), the coefficient of efficiency (E) and the average relative variance (ARV). These estimators are not biased by the variation range of its elements. These are used to determine how the model is able to explain the total variance of the data. The percent standard error of the prediction is defined as:

$$\%SEP = \frac{100}{\overline{y_k}} \sqrt{\frac{\sum_{k=1}^{N} (y_k - y_k)^2}{N}}$$

Where y_k is the observed input k of the pattern; y_k is the estimate output for the pattern; N is the total number of the generalization patterns and $\overline{y_k}$ is the mean value of the observed outputs for the prediction set.

The coefficients *E* and *ARV* are expressed by:

$$E = \frac{S_{obs} - S}{S_{obs}};$$

$$ARV = \frac{S}{S_{obs}}$$

$$S_{obs} = \sum_{k=1}^{N} (y_k - \overline{y_k})^2;$$

$$S = \sum_{k=1}^{N} (y_k - y_k)^2;$$

Where S_{obs} is the measure of the variability of the observed values from their means and S is the measure of the association between the predicted and observed values. For a perfect matching, R^2 and E should be close to 1.0 and the values of % SEP and ARV close to 0.

RESULTS AND DISCUSSION

All the results obtained from the models are presented in this section.

The Table 2 shows the statistical data for the calibration and validation of the mechanistic model. It can be seen that the adjustment for the model is satisfactory. It is defined by the coefficient R^2 (For a perfect matching, R^2 must be equal to one). The selected parameters for the calibration were adjusted until the simulation reported good agreement with the measured data. The last evaluation of the calibration is the validation, which is the comparison between the simulated data and the measured data that have not been used for the model. In this sense it can be seen that R^2 is acceptable.

The CFD solution obtained for temperature can be related with the renovation air index and resembled the measured data within 9 %. The results of Campen and Bot (2003) resembled the experimental data within 15 %.

TABLE 2. Mechanistic model simulation adjustment results showing values for the coefficient of determination R^2 for internal temperature Ti.

	R^2
Simulation	0.7173
Calibration	0.8923
Validation	0.9205

Figure 2 shows the comparison graph for the inner temperature prediction along a complete day. It shows a good approximation for both models and can be seen a slight difference under the measured temperatures except for the CFD predictions at higher temperaures. This slight difference can be cause by low values in the parameters for the mechanistic model and by the wind direction for the CFD model that considers the wind direction parallel to the plane of simulation. The Table 3 shows the statistical results for both models. It can be seen that the predicted results are good. For a perfect matching, R^2 and E should be close to 1.0 and the values of % SEP and ARV close to 0. However, the mechanistic model has better accuracy than the CFD. Even though, both models can be used to design engineering tools to control the greenhouse inner climatic conditions. As a conclusion, it can be said that the behaviour of both models were similar.

Tap (2000) found a similar behaviour for the greenhouse inner temperature, however, in this work both models were tested under different climatic conditions (i.e. high levels of solar radiation).

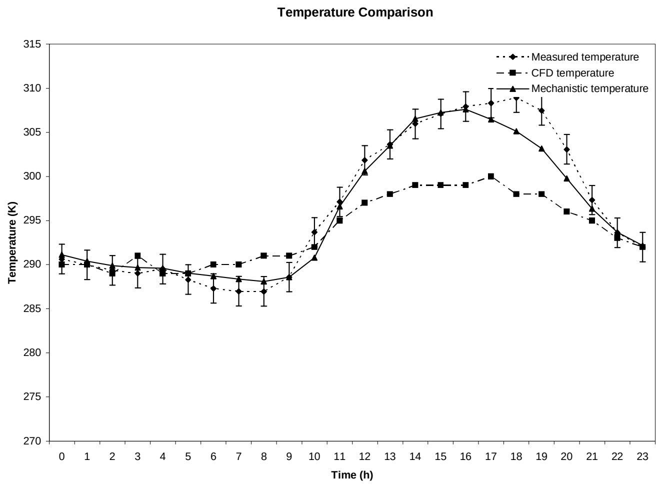

FIGURE 2. Inner temperature behaviour in the greenhouse according to a measured data, mechanics method and CFD predictions. The points for the measured data are the mean value of five minutes readings. Each reading was taken every 30 seconds.

TABLE 3. Model comparison results showing values for the coefficient of determination R2, percent standard error of the prediction (% SEP), the coefficient of efficiency (E) and the average relative variance (ARV) for internal temperature Ti.

Model		Validation		
	R^2	E	% SEP	ARV
CFD	0.9412	0.5878	1.7312	0.4122
Mechanistic	0.9706	0.9574	0.5567	0.0426

Finally, the results for both models are good, according to the statistical data (Table 3), as long as we remember the complexity of the greenhouse system and the variation of the measured variables. (Figure 3).

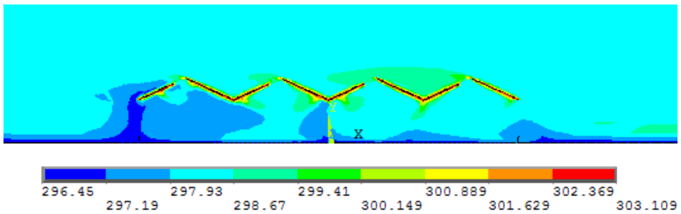

FIGURE 3. Simulated inner temperature patterns in the greenhouse according to CFD method.

This model is only valid under mild operation conditions. That is, the reliability is much lower under high wind velocities. Bot (1983) and Van Henten (1994) concluded that this kind of models is strongly influenced by the wind velocity.

CONCLUSIONS

The comparison results for both models are good and both models can be used to design engineering tools for greenhouse under Mexican climatic conditions.

The mechanistic model is able to be used as a part of an intelligent system to control the inner climatic conditions within the greenhouse.

The CFD model needs more improvement to gain useful knowledge about the inner climatic conditions, as three-dimensional simulations and consider a transient model.

The temperature results obtained from the CFD model are really helpful because it shows a complete pattern of temperatures inside the greenhouse (Figure 3), whereas the mechanistic model supposes a homogeneous temperature within the entire greenhouse.

On the other hand, the CFD methodology seems to be a cumbersome way of predicting the greenhouse climatic conditions; on the contrary, the mechanistic model has the ability for a rapid response.

LITERATURE CITED

BAKKER, J.; BOT, G.; CHALLA, H.; DEBRAAK, N. V. 1995. Greenhouse climate control: an integrated approach. Wageningen Pers. The Netherlands. 279 p.

BARTZANAS, T.; BOULARD, T.; KITTAS, C. 2002. Numerical simulation of the airflow and temperature distribution in a tunnel greenhouse equipped with insect-proof screen in the openings. Computers and Electronics in Agriculture

34(2002): 207-22.

BOULARD, T.; KITTAS, C.; ROY, J. C., P.; WANG. S. 2002. Convective and ventilation transfers in greenhouses, part 2: determination of the distributed greenhouse climate. Biosystems Engineering 83(2): 129-147.

CAMPEN, J. B.; BOT, G. P. A. 2002. Determination of greenhouse-specific aspects of ventilation using tree-dimensional computational fluid dynamics. Biosystems Engineering 84(1): 69-77.

CUNBA, J. B.; RUANO, A.; COUTA, C. 1992. Identification of greenhouse climate dynamic models. Computer in Agriculture, 43: 1-10.

FATNASSI, H.; BOULARD, T.; BOUIRDEN, L. 2003. Simulation of climatic conditions in full-scale greenhouse fitted with insect-proof screens. Electronics and Forest Meteorology 118(2003): 97-111.

JONES, J. W.; HWANG, Y. K.; SEGINER, I. 1995. Simulation of greenhouse crops, environment and control. Acta Horticulturae, 399: 73-86.

MISTRIOTIS, A.; ARCIDIACONO, C.; PICUNO, P.; BOT. G. P. A.; SCARASCIA-MUGNOZZA, G. 1997. Computational analysis of ventilation in greenhouses at zero and low-wind-speeds. Agricultural and Forest and Meteorology 88: 121-135.

MOLINA-AIZ, F. D.; VALERA, D. L.; ALVAREZ, A. J. 2004. Measurements and simulation of climate almeria-type greenhouse using computational fluid dynamics. Agricultural and Forest and Meteorology 125(2004): 35-51.

OULD KHAOUA, S. A.; BOURNET, P. E.; MIGEON. C.; BOULARD, T.; CHASSÉRIAUX, G. 2006. Analysis of greenhouse ventilation efficiency based on computational fluid dynamics. Biosystems Engineering 95(1): 83-98.

RICO-GARCÍA, E.; REYES-ARAIZA, J. L.; HERRERA-RUIZ, G. 2006. Simulation of two different greenhouses inner climate. International symposium on greenhouse cooling, Almeria, Spain.

TAP, F. 2000. Economics-based optimal control of greenhouse tomato crop production. PhD thesis. Wageningen Agricultural University. The Netherlands. 127 p.

TAVARES, C.; GONCALVES, A.; CASTRO, P.; LOUREIRO, D.; JOYCE, A. 2001. Modelling an agriculture production greenhouse. Renewable Energy, 22: 15-20.

UDINK-TEN-CATE, A. J. 1983. Simulation models for greenhouse climate control. In Proceedings, 7th IFAC Symposium. Identification and System Parameter Estimation, York, England. Pergamon, Oxford.

VAN-HENTEN, E. J. 2003. Sensitivity analysis of an optimal control problem in greenhouse climate management. Biosystems Engineering, 85: 335-364.