Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)
Available online at www.inia.es/sjar

Spanish Journal of Agricultural Research 2008 6(2), 189-198
ISSN: 1695-971-X

# Experimental results and modelling of humidity control strategies for greenhouses in continental and coastal settings in the Mediterranean region. I: Experimental results and model development

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## Abstract

Experimental strategies for controlling humidity were compared in a greenhouse sited in Madrid, a continental site in the Mediterranean region. Small roof window apertures significantly reduced the relative humidity with only a limited increase in associated energy consumption. A simplified climate model with four energy exchange terms (heating, insolation, losses through structure, and losses through windows) and three mass exchange terms (evapotranspiration, losses through structure, and losses through windows) was validated, allowing relative humidity to be predicted with an error of < 9%.

**Additional key words**: energy consumption, heating, moisture content, ventilation.

## Resumen

**Resultados experimentales y modelización de estrategias de control de la humedad en invernaderos de zonas continentales y costeras del área mediterránea. I: Resultados experimentales y diseño del modelo**

Se ensayaron una serie de estrategias experimentales para el control de la humedad en un invernadero de Madrid, España. Se comprobó que pequeñas aperturas de la ventana cenital reducían significativamente el nivel de humedad con limitados incrementos del consumo de energía en calefacción. Se validó un modelo climático simplificado con cuatro términos de intercambio de energía (calefacción, radiación solar, pérdidas a través de la cubierta y pérdidas a través de las ventanas) y tres términos de intercambio de humedad (evapotranspiración, pérdidas a través de la cubierta y pérdidas a través de las ventanas), modelo que permitió predecir la humedad relativa con un error inferior al 9%.

**Palabras clave adicionales**: calefacción, consumo energético, higrometría, ventilación.

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Received: 01-09-07; Accepted: 29-04-08.

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Abbreviations used: *A* [water vapour exchange coefficient (evapotranspiration), g kg$^{-1}$ W$^{-1}$ m$^{2}$ h$^{-1}$], *B* [water vapour exchange coefficient (evapotranspiration), h$^{-1}$], *C* (heat capacity, J m$^{-2}$ °C$^{-1}$), *Cwi* (inside air moisture content, g kg$^{-1}$), $Cwi_S$ (inside air moisture saturation, g kg$^{-1}$), *Cwo* (outside air moisture content, g kg$^{-1}$), *H* (heat flux from heaters, W m$^{-2}$), *K* (experimental heat transfer coefficient, W m$^{-2}$ °C$^{-1}$), *RHi* (inside relative humidity, %), *RHo* (outside relative humidity, %), *S* (solar radiation, W m$^{-2}$), *Ti* (inside air temperature, °C), *To* (outside air temperature, °C), *u* (wind speed, m s$^{-1}$), *U* [overall heat transfer coefficient (closed windows), W m$^{-2}$ °C$^{-1}$], *V* [overall heat transfer coefficient (open windows), W m$^{-2}$ °C$^{-1}$], $W_1$ [water vapour exchange coefficient (losses through structure), g kg$^{-1}$ g$^{-1}$ kg h$^{-1}$], $W_2$ [water vapour exchange coefficient (losses through windows), g kg$^{-1}$ g$^{-1}$ kg h$^{-1}$], $\beta$ (fraction of solar radiation converted into sensible heat, non-dimensional), $\tau$ (transmissivity of the cover, non-dimensional).

# Introduction

The effect of air humidity on the growth of greenhouse plants has received relatively little attention. High humidity reduces transpiration and may lead to a loss of crop quality through fungal disease, leaf necrosis, calcium deficiency and the development of soft, thin leaves. Low humidity can lead to water stress (Körner and Challa, 2003). Mortensen (2000) reports that ornamental plants of greater quality are generally produced under lower humidity conditions. Growers usually try to prevent high humidity levels because of the increased risk of disease (Bakker *et al*., 1995).

Growers commonly resort to ventilation as a means of reducing the water vapour content of their greenhouses, although this unfortunately leads to an increase in heat loss and, therefore, in energy consumption; a requirement of future greenhouse systems is that they be more energy efficient (Körner and Challa, 2003). Studies have been conducted to investigate the transient response of greenhouse air conditions to the opening of roof windows (Teitel and Tanny, 1999). De Halleux and Gauthier (1998) reported that proportional ventilation was more effective than on-off ventilation for humidity control in northern latitudes. Seginer and Kantz (1989) showed that a greater fraction of total energy could be saved in mild climates by replacing ventilation with dehumidification. Baptista *et al*. (2001) studied the behaviour of air temperature, humidity and condensation in two greenhouses managed under different natural ventilation strategies under Mediterranean conditions. These authors concluded permanent ventilation to be an effective way of reducing high relative humidity values, and the only option in non-heated greenhouses.

The effects of heating on greenhouse air temperature, humidity and crop temperature have been reported by Teitel *et al*. (1999) and Bartzanas *et al*. (2005). The rate of increase in the humidity ratio and the amplitude of its variation were found to be larger with air heating than with pipe heating. In Mediterranean climates, it seems clear that air heaters (rather than heating pipes) significantly improve the control of the water vapour balance, particularly by keeping the inside air dew point temperature lower than the cover temperature, and so preventing condensation on plastic covers (Kittas *et al*., 2002).

Condensation, transpiration and ventilation are the main vapour fluxes involved in the humidity balance. The influence of condensation has been assessed qualitatively and quantitatively (Pieters *et al*., 1994), but the air flow mode and the energy and mass exchange between crop and greenhouse air are complex (Yang *et al*., 1995). Morris *et al*. (1957) reported that the transpiration rate depended markedly upon the amount of solar radiation. Leaf stomatal resistance can be estimated as a function of the latter. Sensitivity analyses have shown that the influence of solar radiation on greenhouse crop transpiration is much more important than the inside air saturation deficit (Wang and Boulard, 2000; Montero *et al*., 2001), and that the external wind speed and the opening angle of the vents are the most important factors influencing the ventilation flux.

Theoretical models have been developed for describing the energy and water vapour balances of greenhouses (Seginer and Kantz, 1986; Yang *et al*., 1990; Papadakis *et al*., 1994; Wang and Boulard, 2000).

The aim of the present study was to evaluate the factors that influence the water moisture balance in greenhouses in the Mediterranean area, to study how these factors might improve humidity control, and to develop a climate model. This first part of the study was divided into two areas: experimental testing and modelling. In Madrid, greenhouse experiments using heating, ventilation and thermal screens were designed to compare the effect of each combination of technologies on inside relative humidity. A climate model was then constructed using the experimental data obtained and its associated errors calculated.

# Material and Methods

## Greenhouse equipment and recording of data

The Madrid greenhouse had an arched roof, a steel structure, a single layer methacrylate cover, and a North-South ridge orientation. The soil area covered was 132 $m^2$ (6.6 × 20 m, Fig. 1). One side of the greenhouse was shared with another, adjacent greenhouse, although this side was also covered with methacrylate. The distance between the soil and the gutter was 3 m, and the height to the ridge was 4.5 m. The area of methacrylate cover exposed to the outside air was 258 $m^2$. *Gerbera jamesonii* H. Bolus ex Hook (gerbera or African daisy) was grown inside the greenhouse (4 plants $m^{-2}$) in the 2001/02 heating season, and *Helianthus annuus* L. (sunflower; 2 plants $m^{-2}$) in the 2002/03 heating season.

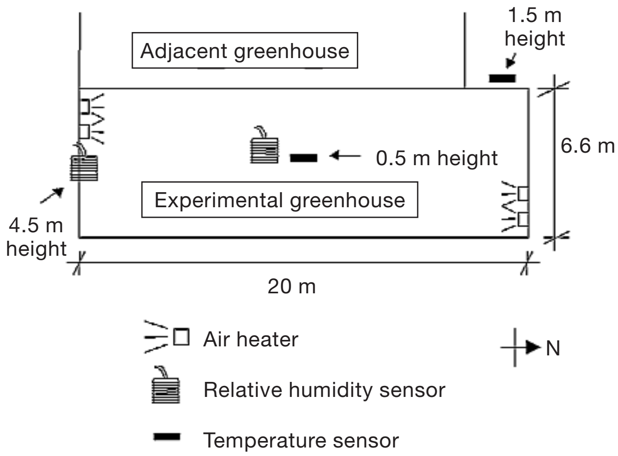


**Figure 1.** Diagram of the experimental greenhouse in Madrid (Spain), showing the air heaters and sensors.

The greenhouse was equipped with four air heaters, a roof window and a thermal screen (Fig. 1). Each of the heaters used 9 kW of electric power and produced a 900 $m^3$ $h^{-1}$ air flow. The roof opening (17.5 m) was continuous, with a maximum aperture of 70 cm. An aluminised thermal screen (composed of 5 strips of 4 m, covering 6.6 × 20 m) was placed at a height of 3 m, providing a nominal 75% shade and a 60% energy saving. The heating system, window and screen were controlled by timers, according to established strategies (see the following section).

Two data acquisition systems (Datataker DT50) were used for recording the climatic variables inside the greenhouse. Data were collected every 5 s. Temperature, solar radiation and wind speed were averaged and recorded every 5 min, and relative humidity every 15 min. Outside air temperature was measured at a height of 1.5 m and inside temperature at 0.5 m using PT100 sensors. Outside solar radiation was measured using a Skye pyranometer. Outside relative humidity was measured at a height of 4.5 m and inside relative humidity at 0.5 m using capacitive sensors. Wind speed was measured at 1 m above the top of the greenhouse (only in the heating season 2002/03). The heat supply was calculated from the hours of heater operation. A condensation sensor was installed in the greenhouse from 21 March to 29 May, 2002. This was made by installing parallel copper tracks on a horizontal plastic support. When a water drop falls on these tracks, it closes an electric circuit and a digital signal is sent to the datalogger; the mean sensor output values were registered every 5 min to determine the periods of the day with the greatest condensation problems.

## Heating, window and thermal screen control strategies

Tests were carried out in Madrid in the heating season 2001/02 (91 d) to compare experimental strategies and for the construction of the climate model, and in the heating season 2002/03 (56 d) to compare experimental strategies and for the validation of the climate model (see the following section).

The period chosen to compare the experimental strategies in Madrid in the season 2001/02 was 1 h (beginning one hour after sunrise in the strategies not involving a thermal screen, and just after sunrise in those with a thermal screen) on 70 selected days. These times were chosen since the problems of condensation are important during these periods when temperatures are low and solar radiation is increasing. Seven strategies (numbered 1 to 7) were tested during these hours, with different window openings and thermal screen combinations (Table 1), all controlled with timers. Each strategy was tested over 10 d, alternating between them but maintaining each strategy for at least 2 d each time; the effect of heating power, ventilation area, and the thermal screen on changes in the relative humidity was recorded. During the night leading up to each measurement time, the heating was connected and the roof window closed. The thermal screen was left unrolled or parked as it would be used during the period tested.

Three main variables were calculated from the data recorded during the mentioned hour:

— The $K$ coefficient (W $m^{-2}$ °$C^{-1}$, with respect to floor area), using the expression $K = H / (Ti - To)$, where H is the heat flux from the heaters (W $m^{-2}$), $Ti$ the inside air temperature (°C), and $To$ the outside air temperature (°C).

— The increase in inside relative humidity at a height of 0.5 m, using the expression $RHi_2 - RHi_1$ (%), where $RHi_2$ is the relative humidity at the end of the hour and $RHi_1$ that at the beginning.

— The increase in inside air temperature at a height of 0.5 using the expression $Ti_2 - Ti_1$ (°C), where $Ti_2$ is the inside air temperature at the end of the hour and $Ti_1$ that at the beginning.

The period selected to compare the experimental strategies (to evaluate the effect of opening the vents for long periods during the night) in Madrid in the 2002/03 season was 05:00 to 09:00 h on 48 selected days. Four strategies (numbered 8 to 11) were tested during these hours, with different window aperture and thermal screen combinations (Table 1). Again, all expe-

**Table 1.** Experimental strategies evaluated in Madrid in the heating seasons 2001/02 and 2002/03, combining air heaters, different roof window apertures, and a thermal screen. The conditions of these last two components are shown together with the measurement features

| Strategy No. | No. of days | Variable heating components | | Measurement features | |
|---|---|---|---|---|---|
| | | Roof window | Thermal screen | Starting hour | Duration |
| *Heating season 2001/02* | | | | | |
| 1 | 10 | Closed | Parked | Sunrise plus 1 h | 1 h |
| 2 | 10 | $0.25 \times 17.5$ m$^2$ | Parked | Sunrise plus 1 h | 1 h |
| 3 | 10 | $0.70 \times 17.5$ m$^2$ [a] | Parked | ½ h before sunrise | 2 ½ h |
| 4 | 10 | $0.70 \times 17.5$ m$^2$ | Parked | Sunrise plus 1 h | 1 h |
| 5 | 10 | Closed | Unrolled | Sunrise | 1 h |
| 6 | 10 | $0.25 \times 17.5$ m$^2$ | Unrolled | Sunrise | 1 h |
| 7 | 10 | $0.70 \times 17.5$ m$^2$ | Unrolled | Sunrise | 1 h |
| *Heating season 2002/03* | | | | | |
| 8 | 12 | Closed | Parked | 5 a.m. | 4 h |
| 9 | 12 | $0.25 \times 17.5$ m$^2$ | Parked | 5 a.m. | 4 h |
| 10 | 12 | Closed | Unrolled | 5 a.m. | 4 h |
| 11 | 12 | $0.25 \times 17.5$ m$^2$ | Unrolled | 5 a.m. | 4 h |

[a] Strategy no. 3: the roof window was opened for a period of 15 min and then closed for intervals of 30 min (Fig. 3).

riments were controlled with timers. Each strategy was tested over 12 d, alternating between them but maintaining each strategy for at least 2 d each time. The mean values of the $K$ coefficient and of temperature and humidity were calculated.

ANOVA (Statgraph® statistical package) was used to compare the values obtained by the different strategies in both heating seasons.

## Energy and mass balance model

A model based on mass and energy conservation equations was developed to evaluate the control strategies (Perdigones *et al.*, 2006). The fluxes considered in the energy balance (W m$^{-2}$, with respect to floor area) were the following:

— Energy supplied by heating, $H$.

— Energy supplied by insolation, $\beta\, \tau S$.

— Energy losses through the structure, $U\,(Ti - To)$.

— Energy losses through the open windows, $V\,(Ti - To)$, with one coefficient for each of the two roof apertures used: 25 cm and 70 cm.

— Heat storage of the greenhouse, $C\,(dTi / dt)$, where $C$ is the heat capacity of the greenhouse as a thermal mass.

Since the model was dynamic, the sum of the energy fluxes for each interval was potentially different to zero; energy was stored or released by the thermal mass, affecting the value of the inside air temperature in the next period considered. Periods of 5 min were used. This first balance supplied the simulated inside temperature of each period calculated from the parameters of the previous period by the following equation:

$$Ti\ (next\ period) = Ti + [H + \beta \tau S - U\,(Ti - To) - V\,(Ti\text{-}To)]\ t / C$$

where $t$ is the time in seconds of the period considered (5 min).

The moisture content balance involved the following fluxes:

— Evapotranspiration, considered proportional to the insolation and to the saturation deficit: $A\,S + B\,(Cwi_S - Cwi)$. $A$ and $B$ are coefficients related to those of the Penman-Monteith equation (Seginer, 2002) but for water content units (g kg$^{-1}$).

— Moisture losses through the structure: $W_1\,(Cwi - Cwo)$.

— Moisture losses through the open windows: $W_2\,(Cwi - Cwo)$, with one coefficient for each of the two roof apertures used: 25 cm and 70 cm.

This second balance supplied the simulated inside moisture content of each period, calculated from the variables of the previous period using the following equation:

$$Cwi\ (next\ period) = Cwi + [A\,S + B\,(Cwi_S - Cwi) - W_1\,(Cwi - Cwo) - W_2\,(Cwi - Cwo)]\ t$$

where $t$ is the time in hours of the period considered (5 min).

The simulated relative humidity was finally obtained from the temperature and vapour content of each period.

### Identification of model coefficients

The coefficients for the model were calculated using the experimental data (91 d) recorded in Madrid during 2001/02. These were calculated using the data of each day separately (91 data sets). Only the first inside temperature and vapour content values in each data set were used as inside climate inputs for the simulation.

The models were run with iteration employing Microsoft® Excel SOLVER, until reaching the minimum mean absolute difference between the simulated and real inside air temperatures (for the energy balance), and between the simulated and real inside relative humidities (for the water vapour balance). The coefficients related to the energy balance were obtained first, followed by those related to the water vapour balance.

The outside air temperature, relative humidity and solar radiation of each period, the measured heat input, the position of the windows and thermal screen, and the initial inside temperature and vapour content values of each data set, were used as inputs in the calculation of the coefficients; $\beta$ $\tau$, $U$, $V$, $C$, $A$, $B$, $W_1$, $W_2$ were the outputs. Input data were available for every 5 min period. In each iteration, the mentioned coefficients were constant; inside air temperature and moisture content at any period were calculated from the values of the previous period, using all the available data. The absolute error of the iteration was recorded, and then a new iteration with other values of $\beta$ $\tau$, $U$, $V$, $C$, $A$, $B$, $W_1$ and $W_2$ initiated until the error could not be reduced. The results of the process were the coefficients of the iteration with minimum absolute error. All calculations were performed using Microsoft® Excel SOLVER, which allows certain variables to be altered with the aim of minimizing any given error.

### Validation of the model

The model was validated in Madrid using the data of the 2002/03 heating season (56 d). The coefficients used were those obtained in the above procedure, except the coefficients of evapotranspiration $A$ and $B$. These were changed since the crop was gerbera in 2001/02 and sunflower in 2002/03. $A$ and $B$ were recalculated for the 2002/03 season using the procedure described in the previous section.

The inside temperature and relative humidity were calculated using the data set recorded for each day (data available for each 5 min period). Inside climate variables were obtained for the full 56 d and compared with the measured values. This provided the mean absolute errors of the model for temperature, moisture content and relative humidity.

## Results

### Experimental results

Figure 2 shows the condensation sensor measurements recorded in Madrid in the 2001/02 heating season. The mean sunrise time for the March-May period was 7:10 h. The maximum risk of condensation was at 8:25 h, a little over one hour after sunrise. Condensation mainly occurred in May when no heating was provided; it disappeared when the air heaters were functioning. The strategies tested experimentally in Madrid in 2001/02 were evaluated over a 1 h period. Table 2 shows the ANOVA results for strategies 1 to 4 (without the thermal screen) and 5 to 7 (with the thermal screen).

Strategy 1 (with heating, closed windows) acted as a reference for comparison between the strategies without a thermal screen for the 2001/02 season. All the strategies with open windows (strategies 2-4) led to a reduction in internal relative humidity ($RHi_2 - RHi_1$): the reduction in relative humidity achieved with the 25 cm roof vent was 7.1% (Table 2; –4.9% for strategy 1

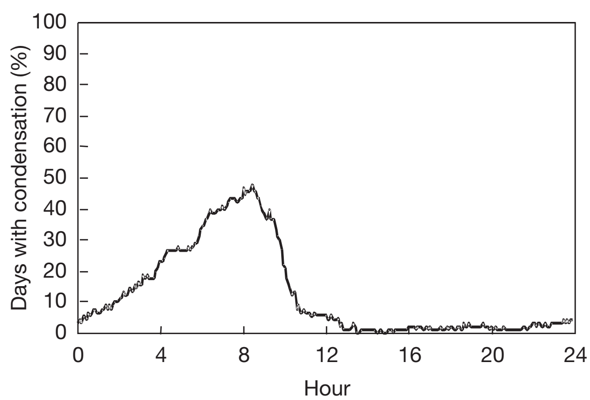


**Figure 2.** Percentage of days with condensation problems in March-May (2001/02 season) and the hour these occurred in the experimental greenhouse in Madrid.

**Table 2.** Experimental results of 2001/02 in Madrid for strategies 1 to 4 (without a thermal screen), for strategies 5 to 7 (with a thermal screen); and experimental results of 2002/03 in Madrid for strategies 8 and 9 (without a thermal screen), and strategies 10 and 11 (with a thermal screen). Each group of strategies was analysed separately. All data are the average values of results obtained during the test periods over the 10 or 12 day experimental period. Temperature and relative humidity sensors inside the greenhouse were placed at a height of 0.5 m. Means with the same letter are not significantly different (significance was set at $P < 0.05$)

| Strategy No. | *Ti* (°C) | $Ti_2 - Ti_1$(1) (°C) | *RHi* (%) | $RHi_2 - RHi_1$(2) (%) | *K* ($W\ m^{-2}\ °C^{-1}$) | *u* ($m\ s^{-1}$) |
|---|---|---|---|---|---|---|
| *Heating season 2001/02* | | | | | | |
| 1 | 20.2 | 3.1 a | 95.7 a | –4.9 a | 11.5 a | — |
| 2 | 15.7 | 3.2 a | 88.8 ab | –12.0 bc | 11.9 a | — |
| 3 | 14.2 | 1.7 ab | 89.2 ab | –14.2 bcd | 15.7 b | — |
| 4 | 13.3 | –2.1 bc | 77.9 b | –21.8 d | 16.7 b | — |
| 5 | 20.9 | –0.2 a | 85.3 | 1.8 a | 10.6 a | — |
| 6 | 19.7 | –2.6 ab | 81.4 | -6.5 ab | 11.4 a | — |
| 7 | 20.9 | –6.1 b | 74.9 | –8.1 b | 13.5 b | — |
| **Strategy No.** | ***Ti* (°C)** | ***Ti – To* (°C)** | ***RHi* (%)** | ***RHo – RHi* (%)** | ***K* ($W\ m^{-2}\ °C^{-1}$)** | ***u* ($m\ s^{-1}$)** |
| *Heating season 2002/03* | | | | | | |
| 8 | 18.0 | 15.7 | 64.7 | 23.3 | 13.6 a | 0.39 a |
| 9 | 19.2 | 13.4 | 61.3 | 35.0 | 16.4 b | 0.18 a |
| 10 | 15.4 | 13.6 | 68.2 | 22.4 a | 10.1 a | 0.08 a |
| 11 | 17.0 | 14.1 | 61.3 | 31.8 b | 11.3 b | 0.04 a |

(1) $Ti_2 - Ti_1$: variation of the temperature during the test hour. (2) $RHi_2 - RHi_1$: variation of the relative humidity during the test hour.

and –12.0% for strategy 2). As the opening area increased, temperatures decreased ($Ti_2 - Ti_1$) and energy consumption increased (*K*) proportionally. In strategy 2 (roof aperture 25 cm), neither the inside temperature nor energy consumption was significantly different to that recorded for strategy 1, but the reduction in relative humidity was significant. In strategies 3 and 4 the same roof aperture was used with a thermal screen; these strategies were compared using two different opening time periods (Fig. 3). The maximum roof aperture of 70 cm, used in strategies 3 and 4, furthered the reduction in relative humidity (–14.2% and –21.8% respectively) but with significant increases in energy consumption.

In the strategies involving the thermal screen, no significant difference in relative humidity was seen between the reference strategy (strategy 5; air heating, windows closed) and strategy 6 (air heating, roof window aperture 25 cm): +1.8% in strategy 5 compared to –6.5% in strategy 6 (Table 2). In strategy 7 (roof window aperture 70 cm) a significant reduction in relative humidity (–8.0%) was obtained, but the energy consumption was higher (13.5 $W\ m^{-2}\ °C^{-1}$ compared to 10.6 $W\ m^{-2}\ °C^{-1}$ for the reference strategy) and a larger temperature variation was seen.

The strategies experimentally tested in Madrid in 2002/03 examined the effect of maintaining the roof vents open (25 cm) while maintaining air heating during the night. The test period was 4 h long, from 5:00 h to 9:00 h. Figure 4 shows the mean reduction in relative

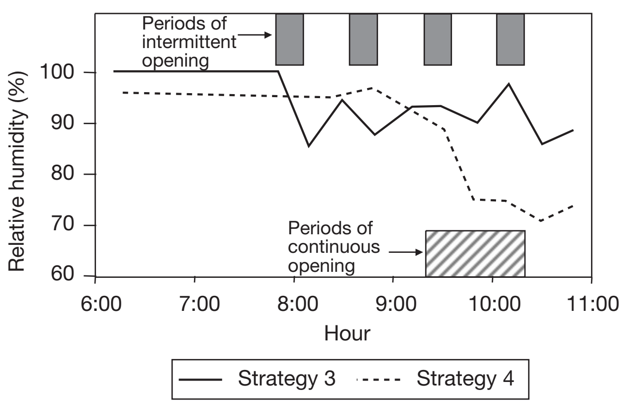


**Figure 3.** Inside relative humidity (measured values) in Madrid (2001/02) over a 5 h period. Result are for: 1) strategy 3, in which the roof window was open (70 cm) for four intervals of 15 min, starting 1/2 h before sunrise, and 2) for strategy 4 in which the roof window was open (70 cm) continuously for 1 h. Values are means for results obtained over 10 d.

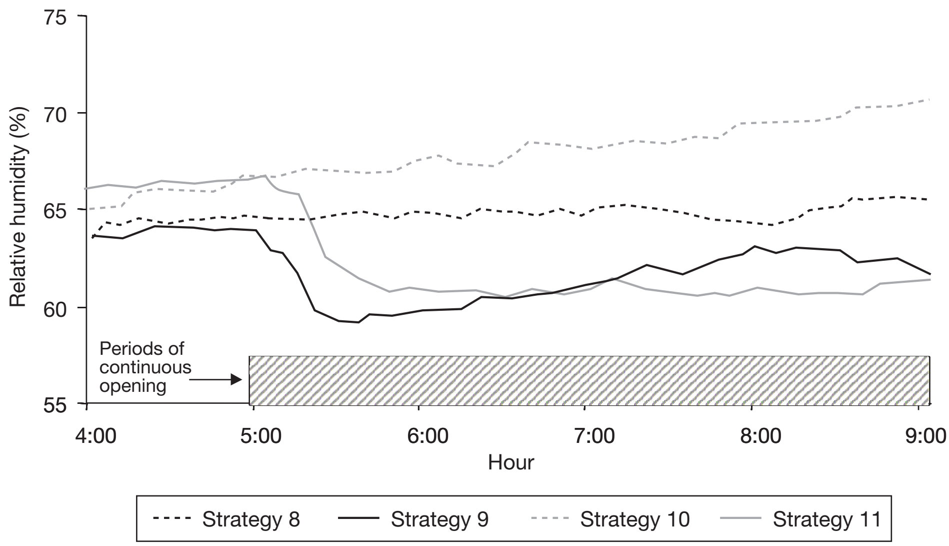


**Figure 4.** Inside relative humidity (measured values) in Madrid (2002/03) over a 5 h period; results are for strategies 8 & 9 (without the thermal screen) and 10 & 11 (with the thermal screen). The roof window (25 cm) was opened at 5:00 h in strategies 9 and 11. Values are the means of results obtained over 12 d.

humidity achieved in each case; this was 3.4% without the thermal screen (Table 2, comparing the 64.7% of experiment 8 and the 61.3% of experiment 9), and 6.9% with the thermal screen (Table 2, comparing the values 68.2% of experiment 10 and 61.3% of experiment 11). The increases in energy consumption were less than 3 W $m^{-2}$ $°C^{-1}$ without the thermal screen, and less than 1.5 W $m^{-2}$ $°C^{-1}$ with the thermal screen (Table 2).

## Modelling

Tables 3 and 4 show the results of the modelling effort. The errors for the climate variables appear in Table 3; Table 4 shows the coefficients for the energy balance and those of the mass balance.

**Table 3.** Mean absolute errors for the temperature, moisture content and relative humidity obtained with the climate model for 91 selected days of the heating season 2001/02 (from 16 October 2001 to 10 May 2002) and 56 selected days of the heating season 2002/03 (from 11 January 2003 to 20 April 2003)

| Mean absolute error | 2001/02 n = 91 d | 2002/03 n = 56 d |
|---|---|---|
| Temperature (°C) | 1.3 | 2.1 |
| Moisture content (g $kg^{-1}$) | 1.2 | 2.0 |
| Relative humidity (%) | 5.7 | 8.8 |

With the data used to calculate the coefficients, the climate model provided a mean absolute error of less than 2°C in the calculation of temperature, less than 1.25 g $kg^{-1}$ in the calculation of moisture content, and less than 6% in the calculation of relative humidity (Table 3, Fig. 5).

An additional batch of data (season 2002/03) was used to validate the model in Madrid, providing an error of less than 2.5°C in the calculation of temperature, less than 2 g $kg^{-1}$ in the calculation of moisture content,

**Table 4.** Coefficients identified for the climate model

| Coefficients | Without a thermal screen | With a thermal screen |
|---|---|---|
| *Energy model* | | |
| $\beta\tau$ (non-dimensional) | 0.31 | 0.30 |
| $U$ (W $m^{-2}$ $°C^{-1}$) | 13.4 | 10.8 |
| $V$ (W $m^{-2}$ $°C^{-1}$)[a] | 2.6 | 1.0 |
| $V$ (W $m^{-2}$ $°C^{-1}$)[b] | 19.5 | 9.3 |
| $C$ (kJ $m^{-2}$ $°C^{-1}$) | 36.2 | 36.2 |
| *Mass model* | | |
| $A$ (g $kg^{-1}$ $W^{-1}$ $m^2$ $h^{-1}$) | 0.018 | 0.018 |
| $B$ ($h^{-1}$) | 0.28 | 0.16 |
| $W_1$ ($h^{-1}$) | 0.12 | 0.12 |
| $W_2$ ($h^{-1}$)[a] | 0.611 | 0.226 |
| $W_2$ ($h^{-1}$)[b] | 2.279 | 0.832 |

[a] Roof window aperture: 25 cm. [b] Maximum roof window aperture: 70 cm.

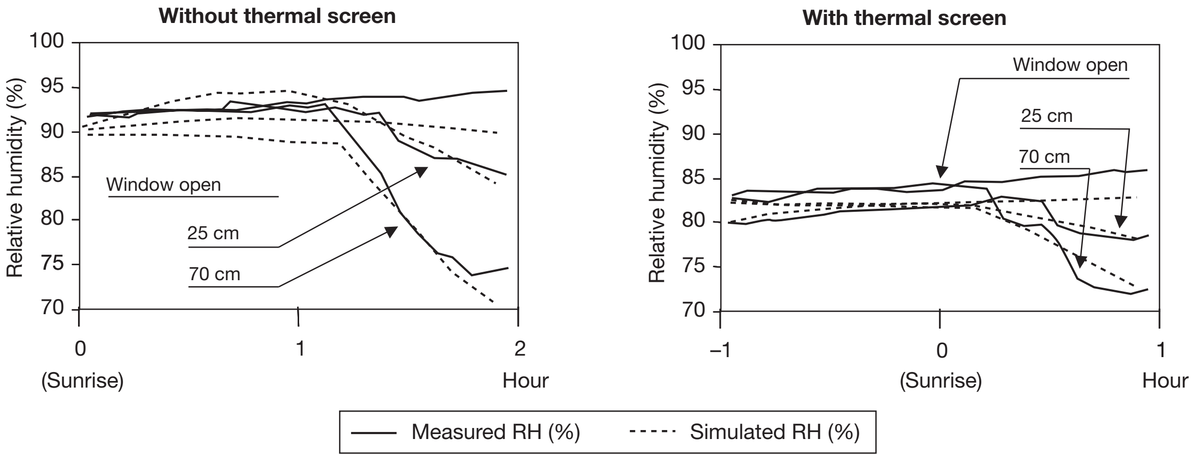


**Figure 5.** Measured and simulated values of inside relative humidity over two hours in the Madrid greenhouse: results are for experimental strategies 1, 2 and 4 (without the thermal screen) and 5, 6 and 7 (with the thermal screen). In the strategies with open windows and no thermal screen, the aperture was opened one hour after sunrise; in the strategies with open windows and with the thermal screen, the aperture was opened at sunrise (aperture = 25 cm in strategies 2 and 6, and 70 cm in strategies 4 and 7). Each curve represents the average values for 10 d.

and less than 9% in the calculation of relative humidity (Table 3, Fig. 6). The variations provided by the model in temperature and relative humidity after opening the window were similar to those actually measured (Fig. 5), and the precision appeared sufficient for the model to be used in simulations of environment control (Fig. 6).

The coefficients of evapotranspiration for gerbera in 2001/02 ($A = 0.018$ g kg$^{-1}$ W$^{-1}$ m$^2$ h$^{-1}$; $B = 0.28$ h$^{-1}$ without the thermal screen, $B = 0.16$ h$^{-1}$ with the thermal screen) were recalculated in 2002/03 for sunflower ($A = 0.002$ g kg$^{-1}$ W$^{-1}$ m$^2$ h$^{-1}$; $B = 0.08$ h$^{-1}$ with and without the screen).

# Discussion

## Experimental results

The combination of air heaters and ventilation allows good possibilities of humidity control, preventing the occurrence of condensation, as Kittas *et al.* (2002) have already shown. The aperture of the vents achieved reductions in relative humidity of 3-8% without the thermal screen, and from 6-9% with the thermal screen; in both cases this decrease was registered in the first hour (2002/03 heating season, Table 2). Maintaining the aperture of the vents for two more hours

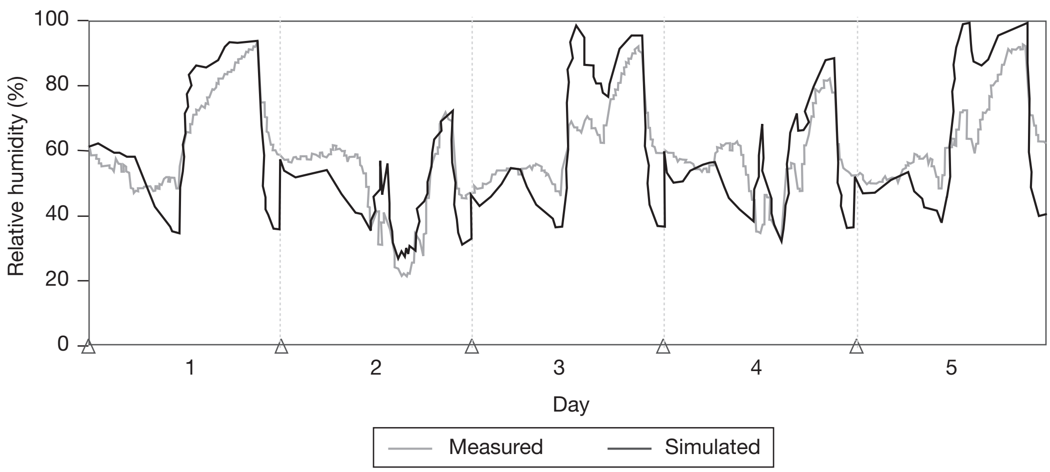


**Figure 6.** Measured and simulated inside relative humidity over five days in Madrid (from 18 to 22 January 2003). Values used in the validation of the model.

did not further reduce the relative humidity (Fig. 4); the transient period (≈ 35 min) was similar in the study of Teitel and Tanny (1999). This would seem to indicate that only the initial period after opening achieves reductions in humidity, and as strategy 3 shows (Fig. 3); when the window is closed the humidity rapidly increases again. An alternative option to permanent ventilation would be intermittent ventilation similar to that used in strategy 3 (Fig. 3). We recommend permanent ventilation in mild climates, in agreement with Baptista *et al.* (2001), since temperature variations are smaller.

The main conclusion obtained from these experimental results was that the use of small roof window apertures (25 cm) seems to significantly reduce inside relative humidity for only a small increase in energy consumption (< 3 W $m^{-2}$ $°C^{-1}$) under the conditions of Madrid.

### Modelling

The results suggest this model is useful for performing simulations of control strategies. Some limitations were observed in the coefficients employed in the model. For example, the values obtained depended on the season of the year; in Madrid, the coefficients obtained in winter 2001/02 (from November to March) were less appropriate for spring 2002 (April and May) and *vice versa*. In particular, the resulting $\beta\ \tau$ value was higher in spring than in winter. This could be due to the differences in the inclination of the sun; transmittance is higher when radiation is perpendicular to the cover.

However, the coefficients obtained with the whole data set for 2001/02 worked reasonably well in 2002/03 (with the error values mentioned above). With this kind of model, the calculation of the coefficients with data from at least one whole heating season is probably required to achieve a reasonable level of error in the following heating season. The main advantage of the modelling method used is the possibility of calculating the coefficients with the Microsoft® Excel SOLVER tool; for both scientists and growers this allows the easy use of data from the previous heating season. Similar models, such as that used by Trigui *et al.* (2001), require the determination of the coefficients by regression.

Condensation is one of main moisture fluxes in greenhouses, but it was not included in the mass balance equation. The main reason was that the balance supplied good results without the condensation flux. In our opinion, the condensation flux should be included if the condensation water is extracted from the greenhouse (not the present case). If it is not extracted the water drops maintain a moisture reservoir inside the greenhouse. Its associated mass must not be included in the balance as a loss of moisture.

In conclusion, this simplified climate model with four energy exchange terms (heating, insolation, losses through structure and losses through windows) and three mass exchange terms (evapotranspiration, losses through structure and losses through windows) simulates inside relative humidity with errors of less than 9%. Similar models require the determination of their coefficients by regression. The proposed model is therefore the simplest for evaluating humidity control strategies.

## Acknowledgements

Funding for this research was provided by the Spanish Ministry of Science and Technology (MCYT), AGL2005-06492.

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