Comparative Tests and Modelling of Humidity Control Strategies in Mediterranean Greenhouses Placed in Continental and Coastal Sites

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Abstract

Comparative tests for humidity modelling were carried out in Mediterranean greenhouses placed in Spain, in Madrid (continental climate) and Cabrils, Barcelona (coastal climate). Small roof window apertures reduced significantly the measured values of inside relative humidity without significant increases of energy consumption. A simplified climate model with four terms of energy exchange (heating, insolation, losses through structure and losses through windows) and four terms of mass exchange (transpiration, evaporation from soil, losses through structure and losses through windows) was adjusted; it allowed the simulation of inside relative humidity with errors lower than 5% in both locations.

INTRODUCTION

The effect of air humidity on the growth of greenhouse plants has been given relatively little attention, but it has been reported that higher ornamental plant quality was generally produced under lower humidity conditions (Mortensen, 2000). Although a high humidity is not always a problem as far as plant growth is concerned, growers try to prevent high values because of the increased risk of diseases (Bakker et al., 1995). Usually, growers have to dehumidify by ventilation to decrease vapour content, leading to an increase in energy consumption. Theoretical and experimental studies have been conducted to investigate the transient response of the greenhouse air conditions to the opening of roof windows. Under Northern latitudes, de Halleux and Gauthier (1998) reported that proportional ventilation was more effective than on-off ventilation for humidity control. Seginer and Kantz (1989) showed that a larger fraction of total energy could be saved in mild climates by replacing ventilation with dehumidification.

The effects of pipe and air heating methods on greenhouse air temperature, humidity and crop temperature have been reported (Teitel et al., 1999). The rate of increase in humidity ratio and the amplitude of its variation were larger with air heating than with pipe heating. In Mediterranean climates, it seems clear that air heaters significantly improve (with respect to heating pipes) the control of the vapour balance, particularly by keeping the inside air dew point temperature lower than the cover temperature and preventing the occurrence of condensation on the 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 qualitative and quantitatively (Pieters et al., 1994), but the air flow mode and the energy and mass exchange between crop and greenhouse air have been found to be complex. It has been reported that transpiration rate depended markedly upon the solar radiation. Leaf resistance can be estimated as a function of solar radiation; in some studies it showed no dependence on vapour pressure deficit or temperature (Montero et al., 2001). Sensitivity

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analysis showed that the influence of solar radiation on crop transpiration was much more important than inside air saturation deficit.

Theoretical models have been developed for describing the energy and water vapour balances (Papadakis et al., 1994); greenhouse simulation models have been also used to estimate the potential of control strategies (de Zwart, 1997; de Halleux and Gauthier, 1998). The existence of computer control systems for environmental management provides the opportunity for better climate conditions and productivity. Studies to develop humidity controllers related to incident radiation have been reported.

The aim of the present study was to evaluate the factors that influence the water vapour balance in Mediterranean greenhouses, to study how these factors might improve humidity control, and to use climate models to analyze improved control strategies. The study was carried out in cooperation between research centres of Madrid and Cabrils (Spain), with different climate conditions. It was divided into two parts: experimental testing and modeling. Firstly, greenhouse experiments using heating, ventilation and thermal screen were designed to compare the effect of each combination of technologies on inside relative humidity. Climate models were then adjusted using experimental data, both in continental and coastal climate conditions. The model obtained can be used to evaluate humidity control strategies.

MATERIALS AND METHODS

The experimental greenhouse of Madrid had an arch-shaped roof, a steel structure and a single layer cover of metacrylate. The covered soil surface was 132 m². The height from soil to gutter was 3 m, and the area of metacrylate cover exposed to the outside air was 258 m². The greenhouse was equipped with four air heaters, side and roof windows and thermal screen; all the equipment was controlled with timers. Gerbera jamesonii was grown in pots inside the greenhouse. The height of the crop was lower than 0.5 m. Two data acquisition systems (Datataker DT50) were used for recording climate parameters inside and outside the greenhouse; air temperature was measured in the centre of the greenhouse with a PT100 sensor, and relative humidity with a capacitive sensor, at a height of 0.5 m; outside temperature was measured with a PT100 sensor, and outside global radiation with a "Skype Instruments" pyranometer, also at a height of 1.5 m, and outside relative humidity with a capacitive sensor, at a height of 1 m above the roof of the greenhouse. The heating supply was calculated from the hours of functioning.

The experimental greenhouse of Cabrils (Barcelona) had an arch-shaped roof, a steel structure and a single layer cover of EVA film. The covered soil surface was 256 m². The height from soil to gutter was 3 m, and the area of cover exposed to the outside air was 1024 m². The greenhouse was equipped with heating by water pipes and roof window; all the equipment was controlled by a climate computer. There was no crop inside the greenhouse in the period of the experiments. A complete set of inside and outside climate parameters was also registered in a data acquisition system Campbell CR10.

Heating, Window and Thermal Screen Control Strategies

The period chosen to carry out the experiments and measurements in Madrid was one hour, beginning one hour after dawn. It was chosen since the problems of condensation are important in this hour with cold temperatures and rising radiation (Pastor et al., 2002). Ten strategies were tested in this hour, with different combinations of heating, window openings and thermal screen (Table 1); all of them were controlled with timers. Each strategy was tested a number of 10 days, looking for the effect of heating power, ventilation area and thermal screen on the relative humidity variations. The previous night to each measurement, until the hour mentioned, heating was connected and side and roof windows were closed; thermal screen was parked or unrolled equal as in the mentioned hour. The Newman-Keuls test was used (STATITCF statistical package) to compare the values obtained with the different strategies. For experimental evaluation, three main parameters were calculated from measured data in the mentioned hour:
- The ratio \( K (\text{W}/\text{m}^2\cdot\text{ºC}) \)
  \[ K = \frac{H}{(T_i - T_o)} \]
  where \( H \) is the heat flux from heaters (\text{W}/\text{m}^2) based on floor area, \( T_i \) the inside air temperature (ºC) and \( T_o \) the outside air temperature (ºC).

- The increase of inside relative humidity at 0.5 m height in the hour, \( RH_{i2} - RH_{i1} \) (%), where \( RH_{i2} \) is the relative humidity at the end of the hour considered and \( RH_{i1} \) at the beginning.

- The increase of inside air temperature at 0.5 m height in the hour, \( T_{i2} - T_{i1} \) (ºC), where \( T_{i2} \) is the inside air temperature at the end of the hour considered and \( T_{i1} \) at the beginning.

**Modelling. Energy and Mass Balances**

A model based in mass and energy conservation equations was developed to evaluate control strategies. In the energy balance, the fluxes considered were the following:

- Energy supplied by heating, \( H \).
- Energy supplied by insolation, \( \beta \tau S \). \( \beta \) is the fraction of energy going to sensible energy and \( \tau \) is the transmissivity of the cover. The value of \( \beta \tau \) was considered 0.3 without thermal screen and 0.075 with thermal screen, according to the references (Marsh and Singh, 1994) and to the nominal value of shading of the thermal screen, value that was checked experimentally.
- Energy losses through the structure, \( U (T_i - T_o) \).
- Energy losses through the open windows, \( V (T_i - T_o) \). In Madrid there were two coefficients for two roof apertures, 25 cm and 70 cm. In Cabrils there was one coefficient proportional to the roof aperture, that was continuous.
- Heat storage of the greenhouse, \( C \left(\frac{dT_i}{dt}\right) \), where \( C \) is the heat capacity of the greenhouse as a thermal mass.

Since the energy balance was dynamic, the sum of the energy fluxes could be different from zero in each period; energy was stored or released by the thermal mass, affecting the value of the inside air temperature in the next period considered. This first balance supplied the simulated inside temperature of each period calculated from the parameters of the previous period, with the following equation:

\[
T_i \text{ (next period)} = T_i + \left[\frac{H + \beta \tau S - U (T_i - T_o) - V (T_i - T_o)}{C}\right]
\]

The vapour content balance (vapour content, \( C_w \)) included the following fluxes:

- Transpiration, considered proportional to the insolation, \( W_1 S \).
- Vapour losses through the open windows, \( W_2 (C_{wi} - C_{wo}) \). As for temperature, in Madrid there were two coefficients for two roof apertures, 25 cm and 70 cm. In Cabrils there was one coefficient proportional to the roof aperture, that was continuous.
- Vapour losses through the structure, \( W_3 (C_{wi} - C_{wo}) \).
- Evaporation from soil and substrate, considered function of the air relative humidity, \( W_4 (100 - RH_{i}) \).

This second balance supplied the simulated inside vapour content of each period calculated from the parameters of the previous period, with the following equation:

\[
C_{wi} \text{ (next period)} = C_{wi} + W_1 S - W_2 (C_{wi} - C_{wo}) - W_3 (C_{wi} - C_{wo}) + W_4 (100 - RH_{i})
\]

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

**Extraction of the Coefficients**

Coefficients of the models were extracted using part of the experimental data. 70 days were used in Madrid, corresponding to strategies 2, 3, 4, 5, 8, 9 and 10; each day was simulated separately. In Cabrils, 10 successive days were used as one only group, using only the first temperature and vapour content as inside climate inputs of the simulation.

The models were run with iteration employing Microsoft Excel, until reaching the minimum mean absolute difference between the simulated and real inside air tempera-
tures (for the energy balance) and between simulated and real inside relative humidity (for the water vapour balance). The coefficients related to the energy balance were obtained first, and then the coefficients related to the water vapour balance were extracted.

The measured heat input, outside temperature, relative humidity and solar radiation of each period, the position of windows and thermal screen, and the initial inside temperature and vapour content values, were used as inputs to the process; the coefficients $U$, $V$, $C$, $W_1$, $W_2$, $W_3$, $W_4$ were the outputs. All input data were recorded every 15 min in Madrid and every 1 min in Cabrils. In each iteration, inside air temperature and relative humidity were calculated from the values of the previous period of 15 min or 1 min. The global absolute error was registered, and then a new iteration with other values of the mentioned coefficients started until the error could not be reduced. The search procedure was carried out using Microsoft Excel$^R$ SOLVER, which allows certain variables to be altered with the aim of minimizing any given error.

RESULTS

Experimental Results

The strategies experimentally checked in Madrid were evaluated in the period with maximum risk of condensation (one hour, beginning one hour after dawn). The results of the Newman-Keuls test for strategies from 1 to 6 (without thermal screen) and from 7 to 10 (with thermal screen) are shown in Table 2.

Without thermal screen, strategy 2 is the reference (with heating, closed windows). All the strategies with open windows (strategies 3 to 6) produced a reduction of the inside relative humidity (parameter $R_{Hi2} - R_{Hi1}$). In proportion as the opening area increased, temperatures decreased (parameter $T_{i2} - T_{i1}$) and energy consumption increased (parameter $K$). Strategy 3 (25 cm of roof aperture) resulted with interesting behaviour: temperatures and energy consumption were not significantly different with respect to the reference, but the reduction of relative humidity did was significant (-4.9 % for strategy 2 against -12.0 % for strategy 3).

With thermal screen, there were no significant differences between the reference strategy 8 (air heating, windows closed) and strategy 9 (air heating, roof window aperture of 25 cm), although the reduction of relative humidity was different (+1.8 % in strategy 8 against -6.5 % in strategy 9). Again the most safe strategy seemed to be the combination of air heating with the reduced opening of the roof window (25 cm).

Modelling

The results of modelling in both sites (Madrid and Cabrils) are presented in table 3, that shows the errors in the calculation of the relative humidity. Results showed that the climate model can be applied in both sites, with an error in the calculation of $R_{Hi}$ lower than 5%, considering the four mass fluxes mentioned (transpiration, evaporation, losses through the structure and through the windows). Error of the model was calculated as the mean absolute difference between the real and simulated humidity. The dynamics after opening the window showed good precision for control simulation (Fig. 1), and the model was checked to be stable enough to simulate periods until ten days (Fig. 2), with only the first value of temperature and vapour content as inside climate inputs. The model can be simplified using only two fluxes (transpiration and losses through windows), but the mean error increased in 1.1% (table 3), and the model with only two fluxes becomes unstable in simulations of more than one day, producing sometimes illogical results.

CONCLUSIONS

Small roof window apertures (25 cm) reduced significantly the measured values of inside relative humidity without significant increase of energy consumption, in the Mediterranean conditions of the experiments.

A simplified climate model with four terms of energy exchange (heating, insolation, losses through structure and losses through windows) and four terms of mass
exchange (transpiration, evaporation from soil, losses through structure and losses through windows) allowed to simulate inside relative humidity with errors lower than 5%.

The model employed was the simplest model that seemed suitable for evaluating humidity control strategies.

ACKNOWLEDGEMENTS
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Literature Cited


Table 1. Strategies evaluated in Madrid combining air heaters, side and roof windows and thermal screen. Position of each element in the hour of the experiment (starting one hour after dawn until two hours after dawn). The exception was strategy 4 (*) in which roof window was open at four intervals of 15 minutes, starting half an hour before dawn until two hours after dawn. Each strategy was tested 10 days.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Heating (variable power)</th>
<th>Roof window</th>
<th>Side window</th>
<th>Thermal screen</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Off</td>
<td>Closed</td>
<td>Closed</td>
<td>Parked</td>
</tr>
<tr>
<td>2</td>
<td>On</td>
<td>Closed</td>
<td>Closed</td>
<td>Parked</td>
</tr>
<tr>
<td>3</td>
<td>On</td>
<td>0.25 x 17.5 m²</td>
<td>Closed</td>
<td>Parked</td>
</tr>
<tr>
<td>4</td>
<td>On</td>
<td>0.70 x 17.5 m² (*)</td>
<td>Closed</td>
<td>Parked</td>
</tr>
<tr>
<td>5</td>
<td>On</td>
<td>0.70 x 17.5 m²</td>
<td>Closed</td>
<td>Parked</td>
</tr>
<tr>
<td>6</td>
<td>On</td>
<td>0.65 x 17.5 m²</td>
<td>0.30 x 18 m²</td>
<td>Parked</td>
</tr>
<tr>
<td>7</td>
<td>Off</td>
<td>Closed</td>
<td>Closed</td>
<td>Unrolled</td>
</tr>
<tr>
<td>8</td>
<td>On</td>
<td>Closed</td>
<td>Closed</td>
<td>Unrolled</td>
</tr>
<tr>
<td>9</td>
<td>On</td>
<td>0.25 x 17.5 m²</td>
<td>Closed</td>
<td>Unrolled</td>
</tr>
<tr>
<td>10</td>
<td>On</td>
<td>0.70 x 17.5 m²</td>
<td>Closed</td>
<td>Unrolled</td>
</tr>
</tbody>
</table>

Table 2. Experimental results for strategies from 1 to 6 (without thermal screen) and from 7 to 10 (with thermal screen). Both groups were analysed separately. All data are average values of 10 days in the hour considered (one hour, beginning one hour after dawn). Temperature and relative humidity sensors inside the greenhouse placed at 0.5 m height. \( T_{i2} - T_{i1} \) (ºC) and \( RH_{i2} - RH_{i1} \) (%) are the variations of temperature and relative humidity in the hour, respectively. Means with the same letter are not significantly different at probability \( P < 0.05 \) (Newman-Keuls test).

<table>
<thead>
<tr>
<th>EXP</th>
<th>( T_{i} ) (ºC)</th>
<th>( T_{i2} - T_{i1} ) (ºC)</th>
<th>( RH_{i} ) (%)</th>
<th>( RH_{i2} - RH_{i1} ) (%)</th>
<th>( K ) (W·m⁻²·ºC⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.38 A</td>
<td>4.46 A</td>
<td>89.29 AB</td>
<td>3.23 AB</td>
<td>A 0</td>
</tr>
<tr>
<td>2</td>
<td>20.24 B</td>
<td>3.11 A</td>
<td>95.69 A</td>
<td>-4.92 A</td>
<td>11.90 A</td>
</tr>
<tr>
<td>3</td>
<td>15.70 AB</td>
<td>3.17 A</td>
<td>88.83 AB</td>
<td>-12.05 BC</td>
<td>11.49 A</td>
</tr>
<tr>
<td>4</td>
<td>14.22 AB</td>
<td>1.67 AB</td>
<td>89.23 AB</td>
<td>-14.24 BCD</td>
<td>15.73 B</td>
</tr>
<tr>
<td>5</td>
<td>13.31 AB</td>
<td>-2.08 BC</td>
<td>77.92 A</td>
<td>-21.83 D</td>
<td>16.69 B</td>
</tr>
<tr>
<td>6</td>
<td>12.27 A</td>
<td>-6.36 D</td>
<td>82.45 AB</td>
<td>-15.93 CD</td>
<td>26.10 C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EXP</th>
<th>( T_{i} ) (ºC)</th>
<th>( T_{i2} - T_{i1} ) (ºC)</th>
<th>( RH_{i} ) (%)</th>
<th>( RH_{i2} - RH_{i1} ) (%)</th>
<th>( K ) (W·m⁻²·ºC⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>16.42 A</td>
<td>-9.35 A</td>
<td>82.48 A</td>
<td>-2.21 AB</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>20.90 A</td>
<td>-0.20 C</td>
<td>85.29 A</td>
<td>1.82 A</td>
<td>10.59 A</td>
</tr>
<tr>
<td>9</td>
<td>19.74 A</td>
<td>-2.57 BC</td>
<td>81.39 A</td>
<td>-6.54 AB</td>
<td>11.43 A</td>
</tr>
<tr>
<td>10</td>
<td>20.94 A</td>
<td>-6.08 AB</td>
<td>74.95 A</td>
<td>-8.05 B</td>
<td>13.46 B</td>
</tr>
</tbody>
</table>
Table 3. Mean absolute error of the relative humidity (%) obtained from the climate model in Madrid (continental site) and in Cabrils, Barcelona (coastal site)

<table>
<thead>
<tr>
<th>Mass fluxes considered</th>
<th>Greenhouse without thermal screen (Madrid)</th>
<th>Greenhouse with thermal screen (Madrid)</th>
<th>Greenhouse without thermal screen (Cabrils)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transpiration + Losses through windows</td>
<td>5.03</td>
<td>4.98</td>
<td>7.20</td>
</tr>
<tr>
<td>Transpiration + Losses through windows + Losses through structure</td>
<td>5.01</td>
<td>4.71</td>
<td>7.20</td>
</tr>
<tr>
<td>Transpiration + Losses through windows + Evaporation from soil</td>
<td>5.02</td>
<td>4.97</td>
<td>4.85</td>
</tr>
<tr>
<td>Transpiration + Losses through windows + Losses through structure + Evaporation</td>
<td>4.47</td>
<td>4.57</td>
<td>4.78</td>
</tr>
</tbody>
</table>

**Figures**

```latex
\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1}
\caption{Measured and simulated values of inside relative humidity (%) in Madrid, along two hours from dawn. Experimental strategies 2, 3 y 5 (without thermal screen) and 8, 9 and 10 (with thermal screen). In the strategies with open windows, the aperture started one hour after dawn (25 cm of aperture in strategies 3 and 9; 70 cm in strategies 5 and 10). Each curve is the average of 10 days.}
\end{figure}
```
Fig. 2. Example of measured and simulated values of inside relative humidity in Cabrils, along five days of February.