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Experimental results and modelling of humidity control strategies for greenhouses in continental and coastal settings in the Mediterranean region. II: Modelling of strategies

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Abstract

Strategies for humidity control —with and without heating— were evaluated via simulations performed with a previously developed model (see accompanying paper, this issue, part I). With heating, the best strategy combined the use of a humidity setpoint with step control of the roof window, increasing the ventilation in line with the outside temperature. Without heating, the best strategy again combined the use of a humidity setpoint with step control of the roof window, but required ventilation to be increased in line with the inside air temperature.

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. II: Simulación de estrategias de control

Un modelo desarrollado anteriormente (ver parte I, en este número) permitió evaluar nuevas estrategias de control de la humedad por simulación. Con calefacción, la mejor estrategia combinó el uso de una consigna de humedad con el control escalonado de la ventana cenital, aumentando la apertura en función de la temperatura exterior. Sin calefacción, la mejor estrategia también combinó el uso de una consigna de humedad con el control escalonado de la ventana cenital, en este caso aumentando la apertura en función de la temperatura del aire interior.

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

Introduction[1]

Simulation models have been used to estimate the potential of greenhouse climate control strategies (De Zwart, 1997; De Halleux and Gauthier, 1998). The availability of computer control systems for environmental management allows better climate conditions to be obtained and therefore greater productivity to be achieved. Improved control algorithms have been found effective for energy saving (Spanomitsios, 2001; Körner

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[1] 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, %), *S* (solar radiation, W m^{-2}), *Ti* (inside air temperature, °C), *To* (outside air temperature, °C), *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}], β (fraction of solar radiation converted into sensible heat, non-dimensional), τ (transmissivity of the cover, non-dimensional).

and Challa, 2003), and studies to develop humidity controllers related to incident radiation have been undertaken (Zolnier *et al*., 2000). Trigui *et al.* (2001a,b) developed and tested a model to predict the dynamic ambient greenhouse air conditions maximizing crop net profits. Among the climatic variables of their model, temperature and relative humidity are taken into account to predict plant growth.

Perdigones *et al.* (2008 – the accompanying paper) developed a dynamic model based on mass and energy conservation equations to study humidity control strategies. The energy submodel takes into account four energy exchange terms: energy supplied by heating (H; $W\ m^{-2}$), energy supplied by insolation ($\beta\ \tau\ S$; $W\ m^{-2}$), losses through the structure [$U \cdot (Ti - To)$; $W\ m^{-2}$], and losses through the open windows [$V \cdot (Ti - To)$; $W\ m^{-2}$], and provides the inside air temperature of each period from the data for the previous period via the following equation:

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

where C (J °C^{-1} m^{-2}) is the heat capacity of the greenhouse as a thermal mass, and t (s) is the given period of time.

The moisture content balance equation takes into three mass exchange terms: evapotranspiration [$A \cdot S + B \cdot (Cwi_S - Cwi)$; g kg^{-1} h^{-1}] considered proportional to the insolation and saturation deficit (Seginer, 2002), moisture losses through the structure [$W_1 \cdot (Cwi - Cwo)$; g kg^{-1} h^{-1}], and moisture losses through the open windows [$W_2 \cdot (Cwi - Cwo)$; g kg^{-1} h^{-1}]. This supplies the simulated inside moisture content of each period from the data for the previous period via the following equation:

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

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

This expression therefore provides the mass submodel. The simulated inside relative humidity (*HRi,* %) is obtained from the air inside temperature and moisture content of each period by means of a psychrometric chart.

The model requires the input of coefficients depending on the features of the greenhouse: β, τ, U, V, C, A, B, W_1 and W_2. These were calculated by Perdigones *et al*. (2008) for the conditions of an experimental greenhouse in Madrid (a continental site in the Mediterranean region; see accompanying paper).

The aim of this second part of the study was to use a climate model, developed and validated in the first of these sister papers, to asses control strategies. The study was performed in cooperation between research centres in Madrid (continental climate) and Cabrils (Barcelona, coastal climate). The model was used to assess humidity control strategies for the climates of both these areas.

Material and Methods

Simulations

Four sets of simulations were performed with the climate model in the settings of Madrid (40°26'0''N, 3°41'0''O, 667 m, continental site) and Cabrils (41°32'0''N, 2°22'0''E, 112 m, coastal site, province of Barcelona). In all cases the greenhouse coefficients used were those of the Madrid greenhouse with no thermal screen. The crop inside the greenhouse was gerbera, thus the coefficients A and B of evapotranspiration used were those of the 2001/02 heating season in Perdigones *et al.* (2008). Values for the outside climate variables (temperature, relative humidity and solar radiation) were available for a whole representative year with intervals of 10 min for both the Madrid and Cabrils sites. From these data and the climate model described in the introduction of this paper, inside air temperature and relative humidity were calculated for each 10 min interval.

In the first set of simulations, the influence of heating and window setpoints was studied. For the heating system, on/off values of 10/14, 12/16 and 14/18°C were set, with a heat input of 300 W m^{-2}. For the roof windows, on/off values of 22/18, 24/20 and 26/22°C were set. No humidity control was used. A total of nine possible situations were therefore simulated for the two sites.

In the second set of simulations, a heating setpoint of 10/14°C and a window setpoint of 22/18°C were used. Humidity was controlled by simulating on/off ventilation using a fixed roof window aperture of 25 cm. The setpoints for relative humidity were 75/65%, 80/70%, 85/75% and 90/80% (as though a hygrostat were available). The roof window could also be opened when the temperature so demanded; the maximum aperture was 70 cm and the on/off setpoint 22/18°C.

In the third set of simulations, a 70/80% humidity setpoint and a temperature setpoint of 22/18°C were used to control the roof window. These two basic strategies were combined with two possible improvements: 1) Step control of the roof window was employed when the humidity setpoint of 80/70% was reached, with two options: 25 cm or 70 cm (instead of the fixed aperture of 25 cm). The 25 and 70 cm apertures were used depending on whether the outside temperature was above or below 8, 10 and 12°C (25 cm when below these figures and 70 cm when above them). With this strategy, when the humidity setpoint is reached, ventilation is increased as outside temperature increases. 2) Step control of the roof window, with the same two aperture options (25 cm and 70 cm) used depending on the inside relative humidity: setpoints of 75/65%, 80/70% and 85/75% for the 25 cm aperture, and 85/75%, 90/80% and 95/85% for the 70 cm aperture were evaluated. With this option, ventilation is increased as inside relative humidity increases. This strategy is similar to that investigated by de Halleux and Gauthier (1998), who simulated humidity control depending on the dehumidification demand.

The fourth set of simulations involved no heating; the only climate control equipment was the roof window. The following situations were compared: 1) aperture control using temperature data (as though a thermostat were available); 2) permanent ventilation with a fixed minimum aperture of 25 cm, and 3) step control of the roof window (25 or 70 cm aperture) when the humidity setpoint (80%) was reached. The aperture opening depended on the inside temperature: under 4°C = 0 cm, 4-8°C = 25 cm, above 8°C = 70 cm. Ventilation was therefore increased with inside air temperature. The roof window could also be opened when the temperature so demanded in all three of the above situations (maximum aperture 70 cm, on/off setpoint 22/18°C).

All simulations supplied the energy consumption, inside temperature and humidity values, as well as length of time that relative humidity was over 90% for each period. Mean values were obtained for each month and the whole year.

Results

Simulations

The first batch of simulations showed that, as expected, energy consumption depended strongly on the heating setpoints. The window temperature setpoints influenced the relative humidity (Fig. 1). These simulations show the importance in the choice of the temperature setpoint. According to the simulation, every 1°C increase in the setpoint in Madrid resulted in an increase in energy consumption of 50 kWh m^{-2} yr^{-1}.

The second set of simulations quantified the reduction in humidity achieved with the strategy that incorporated

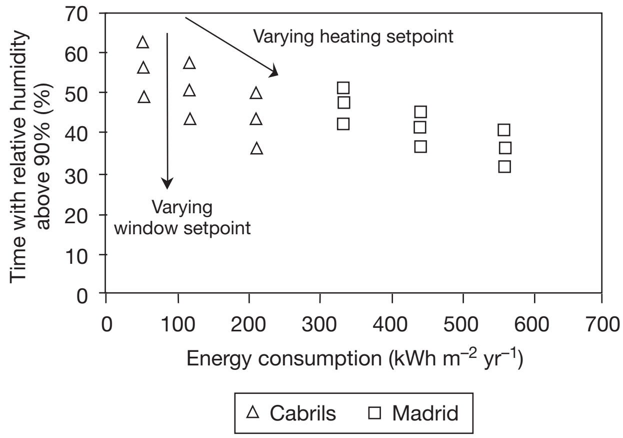

Figure 1. Results of the first set of simulations; relationships between energy consumption and period of high relative humidity (RH), varying heating setpoints (10/14, 12/16 and 14/18°C) and window setpoints (22/18, 24/20 and 26/22°C). The increase in heating setpoint strongly increased the energy consumption; the reduction in the window setpoint reduced the relative humidity. Each point is the average yearly value for one simulation strategy.

a humidity setpoint, using a fixed roof window aperture of 25 cm. The 80/70% setpoint reduced the duration of high relative humidity (> 90%) from 49% to 20% of the time in Cabrils, and from 41% to 16% of the time in Madrid (Fig. 2), with increases in energy consumption ranging from 52 to 58 kWh m^{-2} yr^{-1} in Cabrils (12%) and from 334 to 355 kWh m^{-2} yr^{-1} in Madrid (6%). The reduction in relative humidity was important (although it occurred mainly during the night), with an acceptable

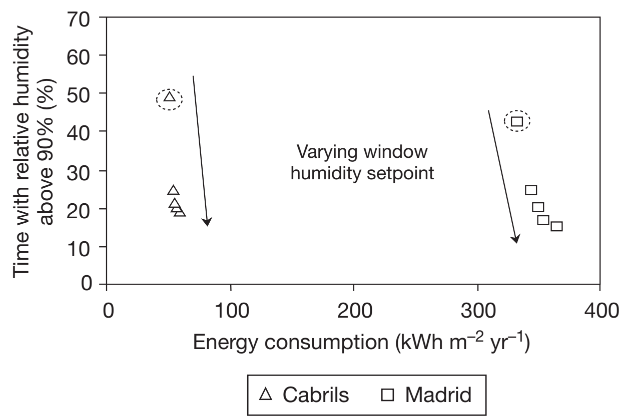

Figure 2. Results for the second set of simulations. Relationships between energy consumption and period of high relative humidity, including aperture opening (25 cm) depending on a humidity setpoint. The circled values are the reference values with no humidity setpoint; for the remaining values, humidity setpoints of 90/80%, 85/75%, 80/70% and 75/65% were used. Obviously, this last value was associated with the lowest humidity levels. Each point is the average yearly value for one simulated strategy.

increase in energy consumption. According to the simulation, the aperture of 25 cm would be unable to reduce the relative humidity to < 90% on many days of the Mediterranean winter; the ventilation achieved with this aperture would not compensate for the evapotranspiration of the crop and soil.

Attempts were made to solve the above limitations of the humidity setpoint in the third batch of simulations by increasing the ventilation in line with the outside temperature or inside relative humidity. Ventilating depending on the outside air temperature led to smaller increases in energy consumption in Madrid (2%) than when ventilating depending on the inside relative humidity (10%). The increase in energy consumption was the same in Cabrils in both cases (13%). The strategy depending on outside air temperature reduced the duration of high relative humidity (> 90%) from 20% to 7% of the time in Cabrils, and from 16% to 7% of the time in Madrid. When ventilating depending on the inside relative humidity, the duration of high relative humidity was shorter (Table 1), although the difference was small. Both strategies reduced the humidity levels during winter days.

The fourth set of simulations quantified the reduction in humidity achieved with the strategies that did not involve heating. Increasing the ventilation obtained better results in the coastal than in the continental setting (Table 2). In Cabrils (coastal climate), strategy 2 (permanent ventilation) reduced the duration of the high relative humidity period from 54% to 23% of the time, and strategy 3 (measuring inside relative humidity) from 54% to 9% of the time. The reduction in mean inside air temperatures was not important (0.1°C for strategy 2, and 0.3 for strategy 3). In Madrid (continental climate), strategy 2 (permanent ventilation) reduced the duration of the high relative humidity period from 73% to 33% of the time, and strategy 3 (measuring inside relative humidity) from 73% to 27%. Strategy 2 was considered unsuitable for a continental climate since it requires the roof window be open (25 cm) even when outside air temperatures are very low (Fig. 3).

Discussion

De Halleux and Gauthier (1998) reported increases in energy consumption of 18.4% in Québec, Canada, when using a dehumidification strategy involving proportional ventilation, similar to that depending on the inside relative humidity used in the present work; the increases in the present study were of 10% in Madrid and 13% in Cabrils. However, ventilation depending on the outside air temperature involves smaller risks; proportionally opening the vents depending on inside relative humidity can lead to the use of the maximum aperture when outside temperatures are very low.

Simulation with the climate model showed the best strategy tested (with heating) combined a humidity setpoint with step control of the roof window, increasing the ventilation depending on the outside temperature. This strategy was useful both in the continental (reducing the duration of the high relative humidity period from 41% to 7% of the time with an increase in energy consumption of 8%) as well as in the coastal setting

Table 1. Results for the third set of humidity control strategies (with heating) at the Cabrils and Madrid sites (coastal and continental climate respectively). Values are for energy consumption and percentage time with high humidity. The first line represents the reference strategy (humidity setpoint for a window aperture of 25 cm and temperature setpoint for a window aperture of 70 cm); comparisons are made with three strategies in which the ventilation was increased as outside temperature increased, and another three in which ventilation was increased as inside relative humidity increased

Window setpoint for 25 cm	Window setpoint for 70 cm	Hours (in %) with RHi > 90%		Energy consumption (kWh m^{-2} yr^{-1})	
		Cabrils	Madrid	Cabrils	Madrid
RHi (80/70%)	Ti (22/18°C)	20	16	58.1	355.4
RHi (80/70%)	Ti (22/18°C) or RHi (80/70%) + To > 8°C	7.4	6.6	65.7	362.5
RHi (80/70%)	Ti (22/18°C) or RHi (80/70%) + To > 10°C	8.5	10.5	58.2	355.8
RHi (80/70%)	Ti (22/18°C) or RHi (80/70%) + To > 12°C	11.8	14.1	57.9	355.5
RHi (75/65%)	Ti (22/18°C) or RHi (85/75%)	6.9	3.3	65.7	390
RHi (80/70%)	Ti (22/18°C) or RHi (90/80%)	8.1	7.6	61.3	376
RHi (85/75%)	Ti (22/18°C) or RHi (95/85%)	16.1	17.8	57.3	364.5

RHi: inside relative humidity.

Table 2. Results for the fourth set of humidity control strategies (without heating) at the Madrid site (continental site) and the Cabrils site (coastal site). Figures represent inside air temperature and percentage time with high humidity. Strategy 1) control only by temperature, strategy 2) permanent ventilation with a fixed aperture of 25 cm, and strategy 3) ventilation depending on humidity setpoint with an aperture of 25 or 70 cm depending on the air inside temperature

Month	Strategy 1				Strategy 2				Strategy 3			
	Inside air temperature (°C)		Hours (in %) RHi > 90%		Inside air temperature (°C)		Hours (in %) RHi > 90%		Inside air temperature (°C)		Hours (in %) RHi > 90%	
	Madrid	Cabrils	Madrid	Cabrils	Madrid	Cabrils	Madrid	Cabrils	Madrid	Cabrils	Madrid	Cabrils
January	5.7	11.6	99	70	5.5	11.4	67	26	5.2	11.1	54	6
February	8.2	12.9	79	62	8.0	12.8	51	20	7.7	12.6	45	3
March	11.9	15.0	71	63	11.8	14.9	18	16	11.7	14.6	13	0
April	13.7	17.0	61	57	13.6	16.9	15	22	13.5	16.7	11	3
May	17.9	18.7	49	50	17.8	18.7	34	19	17.6	18.5	28	5
September	20.4	22.4	34	13	20.4	22.4	9	8	20.3	22.4	6	7
October	11.9	19.4	71	23	11.7	19.3	1	0	11.6	19.3	0	0
November	8.4	15.3	93	68	8.2	15.2	46	37	7.9	15.1	32	25
December	5.3	12.7	99	85	5.1	12.5	59	55	4.9	12.2	53	31
Average	11.5	16.1	73	54	11.3	16.0	33	23	11.1	15.8	27	9

RHi: inside relative humidity.

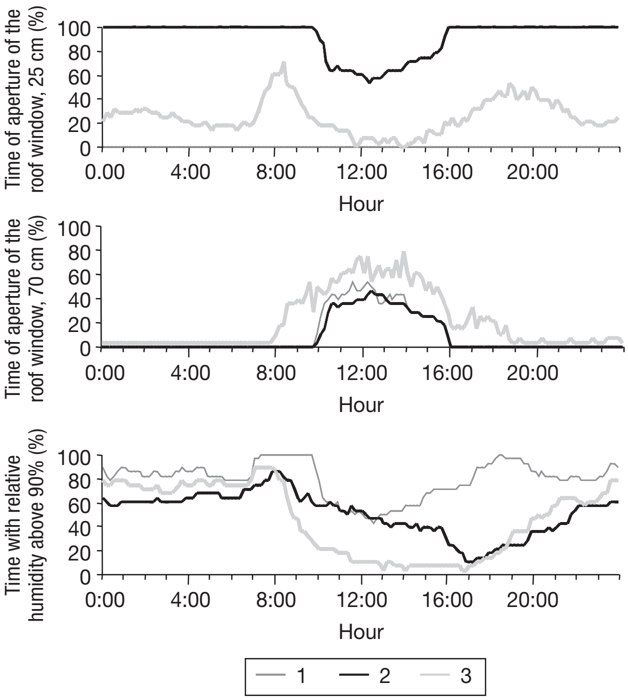

Figure 3. Results of the fourth set of simulations: mean time of opening of the roof window (25 and 70 cm) and percentage of time with relative humidity >90% for the three strategies evaluated without heating. Results are for an average day in February in Madrid. 1) Control by temperature only (with no aperture of 25 cm), 2) Permanent ventilation with fixed minimum aperture of 25 cm, and 3) Step control of roof window with humidity setpoint (80%) and two options depending on inside temperature: 25 cm or 70 cm (instead of the fixed aperture of 25 cm).

(reducing the duration of high relative humidity period from 49% to 7% of the time with an increase in energy consumption of 25%).

When no heating was provided, the best strategy for reducing relative humidity combined a humidity setpoint with step control of the roof window, increasing the ventilation depending on the inside air temperature. This strategy gave better results in the coastal setting (reducing the duration of the high relative humidity period from 54% to 9% of the time) than in the continental setting (reduction from 73% to 27%). In both cases, it seems to improve the permanent ventilation recommended by Baptista *et al*. (2001), also tested in the present study.

In conclusion, these simulations show that the described step control of the window aperture, which requires the use of simple devices (thermostats and hygrostats), can strongly reduce the duration of periods of high relative humidity under the climatic conditions of Madrid and Cabrils compared to on/off control and even permanent ventilation.

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