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Experimental evaluation of a radiant heated floor coupled to an air-to-water heat pump for the cooling of greenhouses

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Abstract

This paper describes the experimental cooling of a greenhouse in Madrid (Spain) using a radiant heated floor (RHF) coupled to an air-water heat pump (HP). Two cooling scenarios were studied over the summers of 2005 and 2006*:* natural ventilation + a shading screen (control system), and natural ventilation + a shading screen + an RHF (concrete) coupled to an air-water heat pump (*i.e.,* in cooling mode; nominal power, 34.1 W m^{-2}). Using the difference between the outside and inside air temperatures, it was concluded that at 0.5 m above the floor the RHF system reduced the temperature by 1.1°C in 2005 and 0.8°C in 2006. Both cooling scenarios were compared with other cooling technologies: the use of the natural ventilation + shading + RHF gave a smaller air temperature difference than fogging at a height equal to or lower than 0.5 m. A model based on the heat pump performance curves was constructed to predict its power consumption and good predictions of the variation over the day were obtained. The power consumption of the heat pump was 104.8 Wh m^{-2} d^{-1} (from 13:00 to 18:00 h) under our test conditions in Madrid. The RHF-HP system may only be appropriate for cooling greenhouses under certain circumstances, *e.g.,* when growing high value crops or when cost is not a limiting factor, as its initial investment cost is about 38 € m^{-2}.

Additional key words: air temperature difference, cooling strategies, heat pump performance modelling, power consumption.

Resumen

Refrigeración de invernaderos mediante suelo radiante asociado a una bomba de calor aire-agua

El suelo radiante es un equipamiento presente en invernaderos comerciales y utilizado convencionalmente como método de calefacción. En este trabajo, en cambio, se ha realizado una evaluación experimental de la refrigeración de un invernadero mediante el uso del suelo radiante acoplado a una bomba de calor aire-agua. Se ensayaron dos escenarios durante los veranos de 2005 y 2006: ventilación natural + malla de sombreo (escenario control), y ventilación natural + malla de sombreo + suelo radiante acoplado a una bomba de calor (escenario de refrigeración activa). Se calcularon las diferencias entre la temperatura del aire interior y exterior (salto térmico), y se concluyó que a 0,5 m sobre el suelo, el sistema suelo radiante-bomba de calor redujo esta diferencia 1,1°C en 2005 y 0,8°C en 2006. Ambos escenarios se compararon con el comportamiento de otros sistemas de refrigeración: se concluyó que el escenario de refrigeración activa obtenía un salto térmico (medido a 0,5 m) más favorable incluso que la nebulización. Se diseñó un modelo basado en las curvas de rendimiento de la bomba de calor para predecir la capacidad refrigerante desarrollada por el sistema suelo radiante-bomba de calor. El consumo energético de la bomba de calor fue 104,8 Wh m^{-2} d^{-1} (de 13:00 a 18:00 h) bajo las condiciones de ensayo. Este sistema parece ser apropiado sólo para refrigerar invernaderos bajo ciertas condiciones, para cultivos de alto valor añadido, cultivos de bajo porte, o cuando el coste de inversión no es un factor limitante ya que éste es aproximadamente 38 € m^{-2}.

Palabras clave adicionales: consumo energético, estrategias de refrigeración, modelización del rendimiento de la bomba, salto térmico.

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Abbreviations used: APC (actual power consumption, W m^{-2}), COP (coefficient of performance), HP (heat pump), HVAC (heating, ventilating and air conditioning), NV (natural ventilation), RHF (radiant heated floor), RPC (rated power consumption, W m^{-2}), T1, T2, T3 and T4 (temperatures measured around the plant, °C), T_i (inside air temperature, measured at a height of 0.5 m, °C), T_o (outside air temperature at 1.5 m above the floor, °C), T_{wb} (greenhouse wet bulb temperature 1.5 m, °C).

Introduction

The cooling of greenhouses is of growing interest, especially in Mediterranean countries where conventional cooling methods cannot provide the optimum conditions for crop growth during the summer months. In recent years this interest has been made manifest in the form of several international meetings of greenhouse technology experts, the main topic of which was cooling systems. One of the last of these was the International Symposium on Greenhouse Cooling held in Almeria by the International Society for Horticultural Science (ISHS, 2006).

Natural ventilation is the most widely used system for removing excess heat, but in the Mediterranean it is commonly insufficient. Further, the rate of ventilation is reduced in greenhouses whose openings are covered by anti-insect screens (Katsoulas *et al.*, 2006). This reduction in ventilation directly influences the greenhouse air temperature (Peeyush *et al.*, 2005). In particular, natural ventilation does not allow a suitable temperature for crop growth to be reached during the summer months. Strategies combining this method with others such as forced ventilation, shading, whitening (Baille *et al.*, 2001) and evaporation systems (Arbel *et al.*, 1999; Katsoulas *et al.*, 2001; Al-Helal, 2007) are therefore required. The search for new cooling technologies that also allow energy savings and/or the use of renewable energy sources is important. One possibility is the use of heating systems that allow the reverse transfer of heat, *i.e.*, that can cool as well as heat the inside of greenhouses.

The use of heat pumps in the achievement of adequate temperatures has been studied by Yildiz and Stombaugh (2006), among others. The modelling performed by these authors shows that heat pumps can be used to help meet heating and cooling needs in closed greenhouses throughout the year. This system has great energy-saving potential when combined with shading. These authors also suggested a strategy for the use of heat pumps that would allow a greenhouse to remain safe from the entry of insects. Heat pumps also control the relative humidity of greenhouse air, and the use of a closed-loop system could allow for water savings over cooling techniques that involve evaporation.

Chou *et al.* (2003) also examined the use of heating systems as a means of cooling greenhouses, and reported the possibility of employing systems of tubes carrying circulating water or vapour, or air generators coupled to heat pumps. These authors simulated the behaviour of a heat pump and found that a 3.7 kW compressor was sufficient to maintain a 240 m^2 greenhouse at 27°C during the day and 18°C during the night (nocturnal set-point temperature) under the climatic conditions of Bangkok.

A radiant heated floor (RHF) is an appropriate system for heating Mediterranean greenhouses that can also provide 20% yearly energy savings over systems such as air heaters (García *et al.*, 1998). The performance of other heating systems for substrate or floor heating has been studied (Rodríguez *et al.*, 2006). The present work proposes the use of the RHF as a method of cooling. Coupled to heat pumps, this technology is already used to provide complete air conditioning for residential buildings. Olesen (1997) studied the possibilities and limitations of this technology in the cooling of houses, taking into account the comfort of their occupants. Although there are differences between greenhouses and other types of buildings, this author concluded that, in glass-walled spaces (in which the entry of solar energy is greater), the maximum cooling capacity of this system was some 100-150 W m^{-2} and happened at midday.

Heating/cooling systems based on radiant panels also provide energy savings compared to convective air conditioning and conventional heating systems. Via numerical modelling, Stetiu (1999) showed that radiant systems could provide energy savings of 30% and up to a 27% reduction in maximum power demand in public and residential buildings.

The aim of the present work was to investigate the use of a RHF coupled to an air-water heat pump (water temperature 10-15°C) for cooling greenhouses in the Mediterranean area. With this purpose, experimental tests were carried out in Madrid in the summers of 2005 and 2006. Then the system was compared to other cooling technologies currently used and the energy demand of the heat pump was modelled. This work is aimed at growers who already have radiant heated floors in their greenhouses. Thus, the alternatives for these growers owning radiant heated floors would be: a) to use the RHF for cooling the greenhouse as well as heating; b) to install an alternative cooling system, *e.g.* fogging. This research tries to guide the growers in their choice between these alternatives, both from a technical and economic point of view.

Material and methods

Experimental greenhouse

Cooling experiments were performed in Madrid (Spain) in a multi-tunnel greenhouse composed of two modules. The upper cross-section of the greenhouse was arched. The steel skeleton was covered in methacrylate sheets; this material transmits from 75% to 85% of visible light and from 0% to 0.5% of infra-red radiation. The floor plan dimensions of the module in which the experiments were performed were 6.6 m × 20 m (area 132 m²). The floor-gutter distance was 3 m, and the floor-roof ridge distance 4.5 m. The total external surface area was 258 m² since the western wall was shared with the adjacent module. With respect to ventilation, the greenhouse had a ridge roof vent running the length of the greenhouse that can open half of the roof. The side vent extended from the gutter down to a height of 2 m above ground and also runs the length of the greenhouse; it is located on the opposite side of the greenhouse to the roof vent.

The crop grown during the experiment was *Gerbera jamesonii* H. Bolus ex Hook (the gerbera or African daisy), an economically important ornamental plant. Plants were grown individually in pots placed directly on the greenhouse floor (four double rows aligned approximately North-South); 25% of the floor surface was covered by these pots, resulting in 4 plants per square metre (distance between row centres 1.6 m). The other 75% of the floor consisted of five corridors for maintenance activities. The plants reached a maximum height of 0.5 m.

Along with other HVAC (heating, ventilating and air conditioning) technologies, the greenhouse was equipped with a concrete RHF (Fig. 1a), installed at the time of construction. This was composed of a 20 mm-thick thermal insulating layer overlain by a network of polyethylene tube reinforced with a metallic structure (distance between tube centres 200 mm, tubes diameter 16 mm) within a 90 mm-thick layer of concrete (the network was situated 45 mm below the surface of the RHF). The density of the polyethylene tubes was 6 m (linear) per square meter of heated floor (450 m of tubing over 90 m²). The refrigerant flowing in the tubes was water. To cool this water, an air-water heat pump (nominal electrical power 4.5 kW) was installed at the beginning of 2005; this was located outside the greenhouse on its north face. This heat pump worked with an on/off control depending on the return water temperature, with set-point at 12°C.

The greenhouse was also equipped with an aluminized shading screen placed at the height of the gutter (3 m); this provided a nominal 75% shading and a 60% energy saving. A previous work (Perdigones *et al.,* 2008) showed that shading screen reduced ventilation rate in the experimental greenhouse by 18.2%.

Two data loggers (*Datataker* DT50), each with five data reception channels, were used to record information. Data logger 1 was used to record the outside radiation level, the outside air temperature, and the internal and external relative humidities. Data logger 2 was used to record the temperature inside the greenhouse at 0.5, 1.5 and 3.2 m from the floor, the temperature of the surface of the RHF, and the temperature in the polyethylene tubes. Every 5 min, the mean value of readings taken every 5 s was calculated.

The inside air temperature was measured using PT100 sensors located at the centre of the greenhouse and at the heights indicated in Figure 1b. These sensors were protected from direct sunlight by a cube of white polystyrene sheets (with the two lateral faces missing). A PT100 sensor was also used to measure the outside air temperature. This was located on the north wall of the

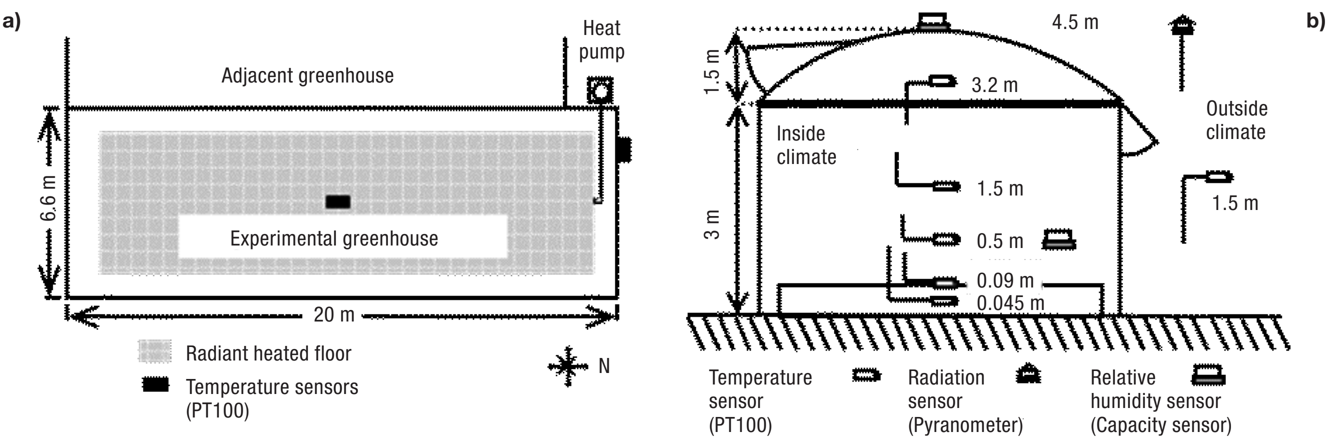

Figure 1. a) Plan view of the experimental greenhouse; location of the heated floor and the air-water heat pump. b) End view of the experimental greenhouse with the sensor system.

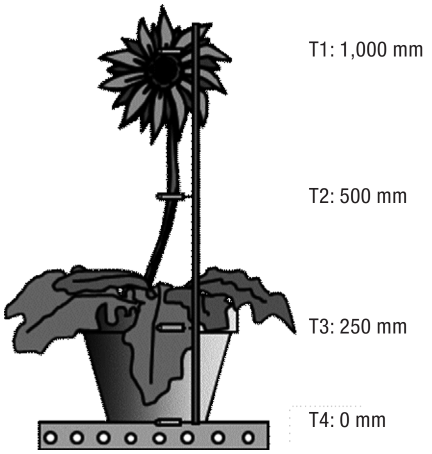

Figure 2. Measurements performed around the plant.

greenhouse at a height of 1.5 m, and was protected from direct sunlight in the same way. Outside radiation levels were measured using a pyranometer (Skye Instruments, model SKS 1110 for measurement of total sunlight) located close by and positioned at the same height as the greenhouse roof ridge. Relative humidity was measured using capacitor sensors; the inside relative humidity was measured at a height of 0.5 m, the outside relative humidity at 4.5 m (over the top of the greenhouse).

On one day in 2005, temperature data were collected in the vicinity of the plants in two pots, one on the RHF, the other still inside the greenhouse but not on the RHF (reference pot). The reference pot was on a part of the floor insulated from the RHF. Temperatures were taken at four different heights (Fig. 2) every 5 s using PT100 sensors; the 5 min mean for each height was then calculated and recorded. The main purpose of these measurements was to test the differences in the substrate temperature.

Cooling strategies

Cooling experiments were undertaken in the summer of both 2005 and 2006. Two scenarios were studied: i) natural ventilation (side and top windows open) + shading screen (reference scenario); ii) natural ventilation (side and top windows open) + shading screen + cooling via the RHF system.

In both years both scenarios were investigated, alternating between them but maintaining each for at least five days each time. There was at least one day between the selected days when alternating reference and cooling strategies. The shading screen was kept permanently extended and both top and side windows were permanently open. On the days when the RHF strategy was used it was left to run over the entire day with an on/off control depending on the return water temperature. In 2005 a total monitoring time of 32 days was amassed, 16 for each cooling scenario; the data collected allowed the characteristics of a representative «average day» to be determined for each. An average day resulted from calculating the mean values in every time gap (5 min) of the 16 days, for the different climatic parameters. In 2006, monitoring time ran for 40 days, from which 16 were selected for each scenario in order to calculate the corresponding average days. The results for the RHF and control scenarios were compared by ANOVA and the LSD test (significance set at $p < 0.05$).

Heat pump performance modelling

Heat pump modelling methods of different complexity exist. Chou *et al.* (2003) took into account the exchanges of mass and heat produced in each of the components of a heat pump in order to calculate its coefficient of performance (COP). In contrast, Willits and Gurjer (2004) employed simpler expressions to estimate the cooling and heating capacities of an air-to-air heat pump. The latter paper was used as a reference for modelling the performance of the present heat pump.

The energy consumption of the heat pump was modelled by developing an expression that would allow its power demands to be predicted. The expression used was based on the performance curves published in the *Hawaii Model Energy Code Application Manual* (Eley Associates, 1994), which adheres to the ASHRAE Standard 90.1-1989: «*Energy efficient design of new buildings except low-rise residential buildings*». This manual offers a series of simple algebraic expressions that determine the power demand during heating and cooling from the nominal power of the heat pump and the environmental conditions. Willits and Gurjer (2004) used these expressions in a study on the use of air-to-air heat pumps for heating and cooling in greenhouses.

In the present work, the electrical power demanded by the heat pump over 10 days during the summer of 2006 (measured at 5 min intervals using an electrical power analyzer) was recorded. The set of 10 days was divided into two groups, the first five days were used to adjust the model, and the last five days were used for validation. The following expression was then used to predict the actual power consumption (APC) of the heat pump in the cooling mode:

$$APC(estimated) = \\ = RPC(A' + B'T_{wb} + C'T_{wb}^2 + D'T_o + E'T_o^2 + F'T_{wb}T_o) \quad [1]$$

where APC is the electrical power demanded (W m^{-2}), RPC (rated power consumption) is the nominal power of the heat pump (in this case 34.1 W m^{-2}), A', B', C', D', E' and F' are adjusted for the heat pump in question, T_{wb} (°C) is the calculated wet bulb temperature inside the greenhouse, and T_o (°C) is the dry bulb temperature of the outside air. The coefficients A', B', C', D', E' and F' were determined by multilinear regression using hourly data for T_o and T_{wb} (from original data collected during 5 days, n = 120). T_o was measured directly; T_{wb}, the inside wet bulb temperature, was determined by linear regression based on the psychometric chart for air. Finally the model was validated using hourly data collected in the other 5 days (n = 120).

Results and discussion

Experimental results

The data collected in the cooling trials were used to estimate two «average days», one for each scenario for the two years. These were characterized using the climatic data shown in Tables 1 and 2. The daily and critical period (13:00-17:00 h; the time when the highest temperatures were reached) means for each variable were determined. Tables 1 and 2 also show the results of the ANOVA and Fisher LSD analysis (significance set at $p < 0.05$) performed on these data.

Regarding the outside climate variables (solar radiation, outside air temperature), no significant differences were seen in cooling scenario respect to the reference scenario, either in 2005 or 2006. Thus, the outside climatic variables would not affect the comparison between two scenarios.

Figures 3a and b show that the mean temperature difference between the floor surface and the pipes was 3°C in the RHF scenario, while in the control scenario there was very little difference. Figure 3a shows that in 2005 the heat pump maintained the temperature of the pipes at 10-15°C in the RHF scenario; Table 1 shows the mean daily temperature was 12.78°C. In the control scenario, however, this temperature was more than 8°C higher.

No significant differences were seen between the inside air temperatures at heights of 0.5, 1.5 and 3.2 m in the two cooling scenarios, either in 2005 or 2006.

Figure 3 also shows a displacement between the maximum values of the climatic variables. Furthermore, the hours for these maxima are shown in Table 3. Maximum floor temperatures with the RHF system occurred earlier than in the reference scenario. In the involved process, solar radiation heated the floor, and the floor, with a certain delay, heated the inside air. The RHF system extracted part of the heat of the solar radiation, and suppressed part of the delay. For this reason, the effect of the RHF caused the maximum inside air temperature at 0.5 m to occur at a time closer to the solar radiation maximum.

Table 1. Daily mean values (MV) and daily standard deviations (SD), and mean values and standard deviations from 13:00 to 17:00 h, for different variables, in the RHF cooling and control scenarios (prepared from data taken over 16 days during the summer of 2005). Results for the ANOVA analysis are shown for the interval 13:00-17:00 h: values with the same letter show no significant differences ($p < 0.05$; Fisher LSD test)

Climatic variable	RHF system (n = 16 days)		Reference (n = 16 days)	
	MV ± SD (13:00-17:00 h)	MV ± SD (00:00-24:00 h)	MV ± SD (13:00-17:00 h)	MV ± SD (00:00-24:00 h)
Solar radiation, W m^{-2}	899.18 ± 132.51[a]	325.74 ± 54.94	916.80 ± 50.30[a]	310.26 ± 35.09
Outside air temperature,°C	33.79 ± 1.78[a]	25.98 ± 2.48	32.22 ± 2.82[a]	23.79 ± 2.59
Pipe temperature, °C	14.36 ± 0.77[a]	12.78 ± 0.63	22.95 ± 1.74[b]	21.28 ± 2.41
Floor surface temperature, °C	17.65 ± 0.90[a]	15.71 ± 0.75	23.18 ± 1.76[b]	21.74 ± 2.08
Inside air temperature 0.5 m, °C	32.37 ± 1.54[a]	24.70 ± 1.95	31.91 ± 2.09[a]	23.83 ± 2.06
Inside air temperature 1.5 m, °C	36.36 ± 2.15[a]	26.54 ± 2.40	35.20 ± 2.51[a]	25.02 ± 2.35
Inside air temperature (0.5 m)-outside air temperature, °C	–1.42 ± 1.07[a]	–1.28 ± 0.89	–0.30 ± 0.99[b]	0.04 ± 0.82
Inside air temperature (1.5 m)-outside air temperature, °C	2.57 ± 1.18[a]	0.56 ± 0.69	2.98 ± 0.95[a]	1.23 ± 0.68

Table 2. Daily mean values (MV) and daily standard deviations (SD), and mean values and standard deviations from 13:00 to 17:00 h, for different variables, in the RHF cooling and control scenarios (prepared from data taken over 16 days during the summer of 2006). Results for the ANOVA analysis are shown for the interval 13:00-17:00 h: values with the same letter show no significant differences ($p < 0.05$; Fisher LSD test).

Climatic variable	RHF system (n = 16 days)		Reference (n = 16 days)	
	MV ± SD (13:00-17:00 h)	MV ± SD (00:00-24:00 h)	MV ± SD (13:00-17:00 h)	MV ± SD (00:00-24:00 h)
Solar radiation, W m^{-2}	830.77 ± 147.83^a	270.90 ± 58.66	767.54 ± 173.63^a	260.60 ± 55.69
Outside air temperature, °C	34.65 ± 4.63^a	26.43 ± 3.67	34.17 ± 2.45^a	26.37 ± 2.37
Pipe temperature, °C	13.42 ± 1.30^a	11.79 ± 1.07	25.86 ± 1.22^b	24.07 ± 1.14
Floor surface temperature, °C	17.26 ± 1.85^a	15.16 ± 1.56	26.13 ± 1.26^b	24.48 ± 1.15
Inside air temperature 0.5 m, °C	33.45 ± 4.38^a	25.54 ± 3.44	33.76 ± 2.17^a	26.30 ± 2.13
Inside air temperature 1.5 m, °C	35.87 ± 4.89^a	26.48 ± 3.74	35.38 ± 2.25^a	26.66 ± 2.24
Inside air temperature (0.5 m)-outside air temperature, °C	–1.20 ± 0.59^a	–0.89 ± 0.49	–0.41 ± 0.77^a	–0.07 ± 0.57
Inside air temperature (1.5 m)-outside air temperature, °C	1.22 ± 0.68^a	0.05 ± 0.45	1.21 ± 0.90^a	0.29 ± 0.56
Outside relative humidity, %	23.72 ± 4.41^a	41.50 ± 5.66	24.62 ± 3.83^a	43.33 ± 6.92
Inside relative humidity, %	32.28 ± 4.55^a	51.09 ± 6.00	29.96 ± 4.69^a	47.86 ± 5.62

The cooling achieved in each scenario was estimated as the difference between the outside and inside air temperatures ($T_i - T_o$, °C; taking the inside air temperature as that measured at 0.5 m and at 1.5 m). Significant differences were detected when the inside temperature was measured at 0.5 m in the summer of 2005. Figure 4a shows the difference at 0.5 m in the RHF scenario to be greater (1.1°C), while Figure 4b shows the temperature difference at 1.5 m to be virtually inappreciable. In 2006 no significant differences were seen at either height, but the difference at 0.5 m was 0.8°C higher in the RHF than in the reference scenario. So we can conclude that only at 0.5 m did the RHF system improve the results obtained with the control system (by 1.1°C in 2005 and 0.8°C in 2006).

Figure 4a shows that the air temperature difference could achieve negative values in the reference condition (naturally vented greenhouse + shading screen). This fact could be explained because of the cooling effect of crop evapotranspiration. Just after sunrise, the evapotranspiration rate increased gradually, as it is considered proportional to the insolation (Seginer, 2002). In the central hours of the day the plants reached their full transpiration while the insolation effect increased, therefore the inside temperature was higher than the

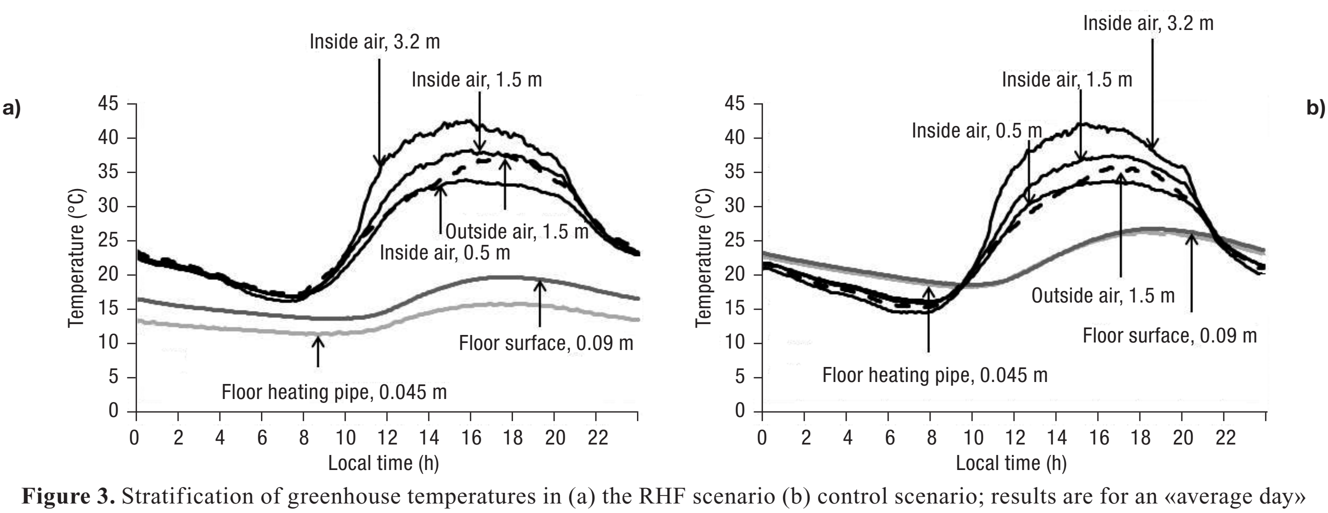

Figure 3. Stratification of greenhouse temperatures in (a) the RHF scenario (b) control scenario; results are for an «average day» (calculated from the data collected over 16 days during 2005).

Table 3. Local hour (h) for maximum value of the climatic variables measured in the trials for the RHF cooling system and the reference situation (16 days each one, summer 2005)

Climatic varible	Local hour (h)	
	RHF system	Reference
Solar radiation, W m^{-2}	14:35	14:10
Outside air temperature, °C	17:45	17:35
Pipe temperature, °C	18:10	19:20
Floor surface temperature, °C	17:40	18:40
Inside air temperature 0.5 m, °C	15:45	16:45
Inside air temperature 1.5 m, °C	16:00	16:40
Inside air temperature 3.2 m, °C	15:55	15:25

outside temperature. In the afternoon, about 17:00 h, the insolation decreases harshly and the air temperature difference became negative again.

No significant differences were seen between the inside relative humidity at a height of 0.5 m in the two cooling scenarios in summer 2006 (Table 2). The RHF system did not cause condensation according to our measurements at a height of 0.5 m: maximum relative humidity in a period of five minutes (16 days) was 87.7% with RHF, and 85.8% without RHF.

The work of Perdigones *et al.* (2008) was used to provide data regarding other cooling strategies (collected in the same experimental greenhouse in 2003). The methods and materials used in this and the present work were similar. This earlier work involved combinations of six cooling systems:

1. Natural ventilation (side and top windows).
2. Natural ventilation (side and top windows) + a shading screen.
3. Natural ventilation + low pressure fogging (cycle:12 s every 4 min; flow: 0.6 L h^{-1} m^{-2}).
4. Natural ventilation + low pressure fogging (cycle: 8 s every 1 min; flow: 1.6 L h^{-1} m^{-2}).
5. Natural ventilation + a shading screen + low pressure fogging over the shading screen (cycle: 8 s every 1 min; flow: 1.6 L h^{-1} m^{-2}).
6. Natural ventilation + a shading screen + low pressure fogging under the shading screen (cycle: 8 s every 1 min; flow: 1.3 L h^{-1} m^{-2}).

In scenarios 2, 5 and 6 the shading screen was permanently extended. In scenarios 3, 4, 5 and 6, fogging took place between 13:00 and 18:00 h.

Table 4 shows the results of this earlier comparative study involving different conventional greenhouse cooling technologies and the results for the RHF scenario of the present study; the variable compared was the temperature difference between the inside air at 1.5 m and that of the outside air. It is desirable this value to have a negative value, which means that the inside temperature is lower than the outside temperature. Natural ventilation + conventional fogging (cycle: 8 s min^{-1}; water flow: 1.6 L m^{-2} h^{-1}) provided the best results, the temperature difference was –0.8°C at 1.5 m.

In Figure 5, the cooling technologies seen before are compared to the RHF-heat pump system at different heights inside the greenhouse. Fogging provided the best results at heights above 0.5 m, but the use of the natural ventilation + shading + RHF scenario gave a better air temperature difference than fogging at a height equal or lower than 0.5 m. Moreover, the relative humidity is lower in the RHF scenario (Table 6), an important climate parameter for the crop health and which must be taken into account in order to avoid undesirable con-

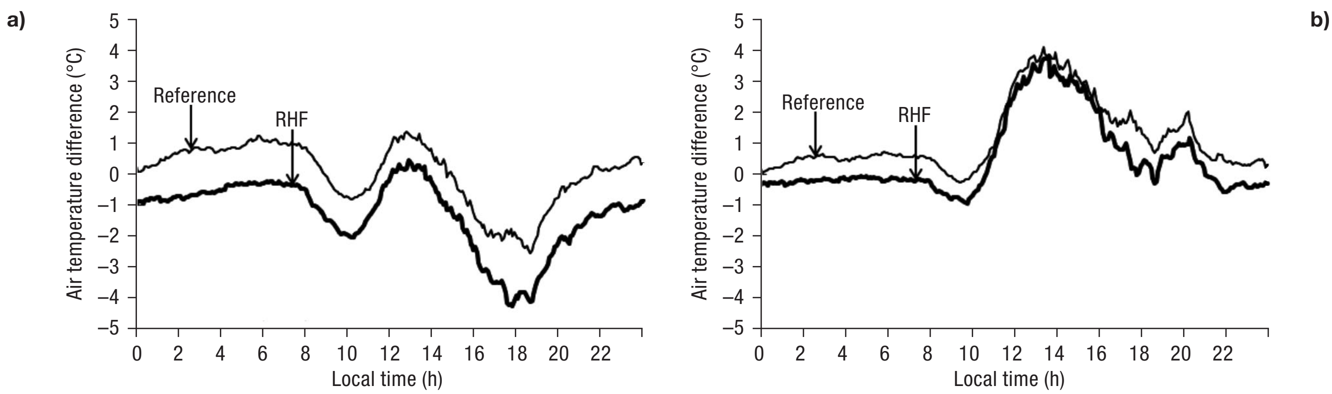

Figure 4. Air temperature difference between the inside air and outside air for an average day under both cooling scenarios (calculated from the data collected over 16 days during 2005). (a) Inside air temperature measured at a height of 0.5 m; (b) Inside air temperature measured at 1.5 m.

Table 4. Cooling obtained with different combinations of systems over 84 days in the summer of 2003 (Perdigones *et al.,* 2008) from 14:00 to 17:00 h. Comparison with the results of the present work, for 32 days of summer 2005 and 32 days of summer 2006 (from 13:00 to 17:00 h)

Cooling equipment	Temperature difference between the inside air (measured at a height of 1.5 m) and the outside air, °C	
Ventilation	+ 3.8	
+ shading screen	+ 2.3	
+ fogging system (0.6 L h^{-1} m^{-2})	+ 1.4	
+ fogging system (1.6 L h^{-1} m^{-2})	– 0.8	
+ shading screen + fogging above the screen (1.6 L h^{-1} m^{-2})	– 0.1	
+ shading screen + fogging under the screen (1.3 L h^{-1} m^{-2})	– 0.7	
	Summer 2005	**Summer 2006**
Ventilation + shading screen	+ 3.0	+1.2
Ventilation + shading screen + cooling concrete floor	+ 2.6	+1.2
	Temperature difference between the inside air (measured at a heigth of 0.5 m and the outside air, °C	
	Summer 2005	**Summer 2006**
Ventilation + shading screen	– 0.3	–0.4
Ventilation + shading screen + cooling concrete floor	– 1.4	–1.2

densation. Regarding economic costs (Table 6), the initial investment is high for the RHF coupled to the heat pump which amounts to approximately 38 € m^{-2}. However, it must be pointed out that this is a reversible system which could meet both cooling and heating needs throughout the year. This fact means that the recovery time of the investment shortens. Previously, in the introduction section, it was already mentioned that the reversible system provides energy savings. In the case of RHF, this aspect was studied for heating by

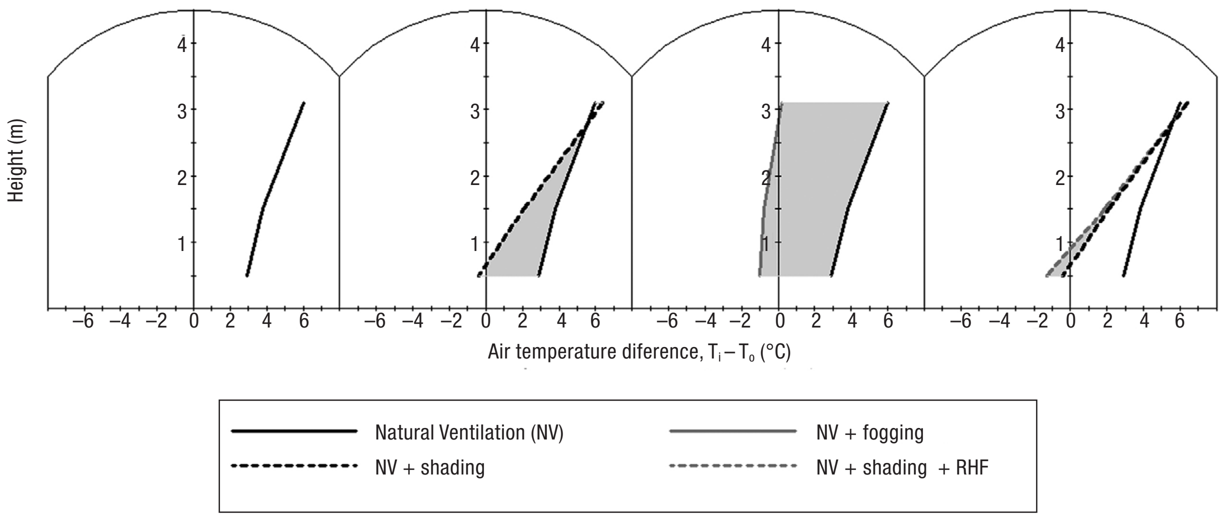

Figure 5. Experimental data: mean values for the critical period 13:00-17:00 h. Graph comparing the air temperature difference obtained from different cooling strategies, $T_i - T_u$ (°C) at different heights. The shaded area shows the improvement of the cooling effect achieved with the addition of technologies.

Table 5. Coefficients used in the model for calculating the actual power consumption (APC) of the heat pump in the RHF scenario

Coefficients	
A'	–0.355
B'	–0.144
C'	0.003
D'	0.102
E'	0.000
F'	–0.001

Perdigones *et al.* (2006); in Table 6, the energy consumption was showed when this system was used for cooling.

The results show the effect of the RHF system to be very limited; it can reduce the air temperature inside the greenhouse by 1°C at 0.5 m height and the effect is higher below this level. In contrast, fogging systems can reduce the temperature of the entire greenhouse by 4°C. A feature of the RHF system is that it allows root cooling (see Fig. 6) and does not increase the absolute humidity ratio in contrast to evaporative cooling methods. Evaporative cooling, *e.g.* fogging, might hinder transpiration in conditions with high relative humidity (Perdigones *et al.*, 2005). The temperature measurements taken close to the plants indicate that at the roots (temperature T3), the RHF system reduces the temperature by some 3°C (Fig. 6). Further studies should be performed on the effect of RHF cooling on root temperature, and on the influence of this on plant health.

The RHF system may only be appropriate for cooling greenhouses under certain circumstances, *e.g.,* when growing high value crops or when cost is not a limiting factor, as the initial investment of this technology is very high (Table 6). Furthermore, the RHF system could be an alternative for greenhouse cooling in regions where the outside relative humidity is high, and the evaporative systems do not work properly.

Heat pump performance

Figure 7 shows the actual power consumption of the heat pump over a normal day (RHF scenario). The hourly mean value never reached the nominal electrical power of 4.5 kW, since the heat pump worked in start/stop cycles due to the on/off control depending on the return water temperature, with setting of 12°C.

A possible improvement in the RHF system is focused on the control system of the heat pump which was based on the return water temperature. As it is depicted in Figure 8, the heat pump operation is parallel to the floor heating pipe temperature: the floor pipe temperature reached a peak at 18:00 h (Table 3) and the APC reached its maximum value at about the same time. However the internal greenhouse temperatures reached «unacceptably» high values already by 16:00 h (Table 3), due to the observed delays inherent in cooling system design. This delay may be reduced by changing the control strategy.

Nevertheless, this improvement based on the change in control strategy of the heat pump may have limitations. If we consider the heat pump to work continuously at full power all day long, the floor pipe temperature would be more constant and closer to 12°C and the floor surface temperature would experience less changes. In the present study, the temperature of water running through the pipes ranged from 11 to 15°C, and the floor surface temperature from 13 to 19°C. Working at full power 24 hours a day, the floor pipe temperature may have ranged from 11 to 13°C, and the floor surface from 12 to 17°C. After all, the element responsible for the cooling of the greenhouse is the floor surface. Therefore, the heat pump at full power would have

Table 6. Cooling equipment costs. Natural ventilation (NV) and fogging: values of 2003; shading and radiant heated floor (RHF): values of 2005. HP: values of 2006. Initial investment cost estimated for a greenhouse with 5000 m2 of covered soil surface

	Natural ventilation (NV)	NV + shading	NV + fogging	NV + shading + RHF
Relative Humidity, 0.5 m height (%)	18.63	27.00	58.60	29.57
Water flow (l m^{-2} d^{-1})	0	0	8.00	Insignificant
Energy consumption(Wh m^{-2} d^{-1})	Insignificant	Insignificant	Insignificant	104.8
Investment (€ m^{-2})	0	1.5	3.0	1.5 (shading) + 15.0 (HP) + 22.5 (RHF)

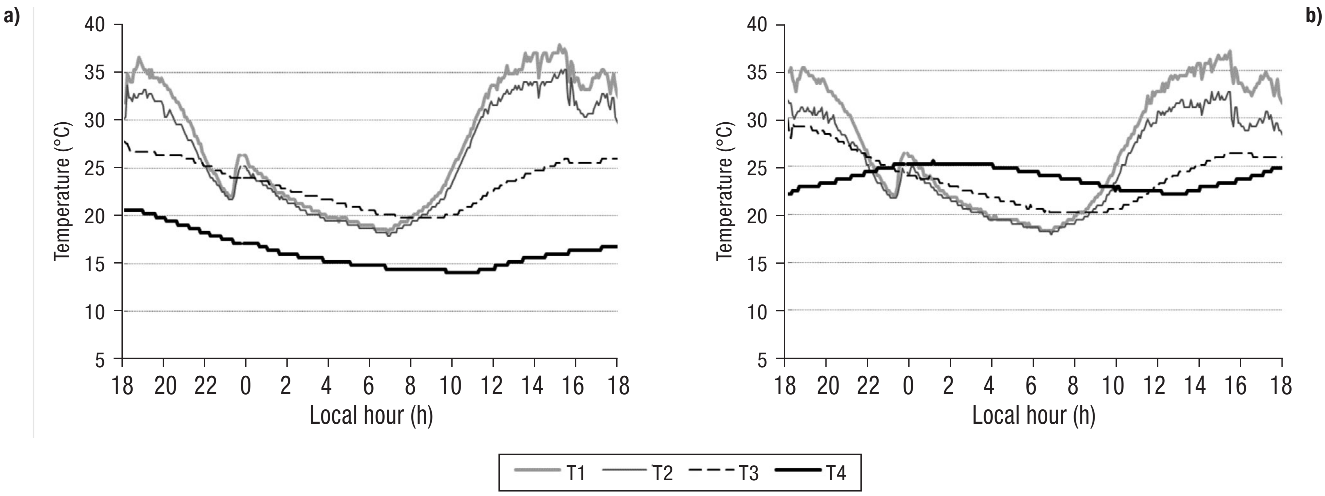

Figure 6. Stratification of temperatures around the plant: (a) RHF scenario (b) control scenario. T1: air temperature at a height of 1 m; T2: air temperature at a height of 0.5 m; T3: substrate temperature next to the roots; T4: soil temperature at the bottom of the plant pot (data collected on a single day in 2005).

improved slightly the heat extraction from the inside air to the RHF, given that the temperature reduction of 6°C (measured in the experimental tests, 2005) for the floor surface resulted in only 1.1°C at a height of 0.5 m; with an additional reduction of 2°C in the floor surface temperature, the air temperature at 0.5 m is not believed to drop significantly lower.

In conclusion, the changes in control strategy of the RHF system did not seem to improve its performance: the combination of shading screens, natural ventilation and a RHF + a HP did not provide the necessary cooling capacity for the experimental greenhouse. Thus, it is not worth considering the implementation of such a system to cool the whole volume of the greenhouse, since this combination of equipment only provides a significant cooling below 0.5 m. This cooling effect could be reinforced with some kind of screening in search of a localized cooling around crops lower than 0.5 m.

Heat pump performance modelling

Table 5 shows the coefficients obtained after adjustment with the 5 days of measured data. Using these coefficients of Eq. [1] for the heat pump APC, the model was used to calculate an estimated APC for 5 additional days.

Using the hourly values obtained over this additional 5-day trial, Figure 9 shows the relationship between

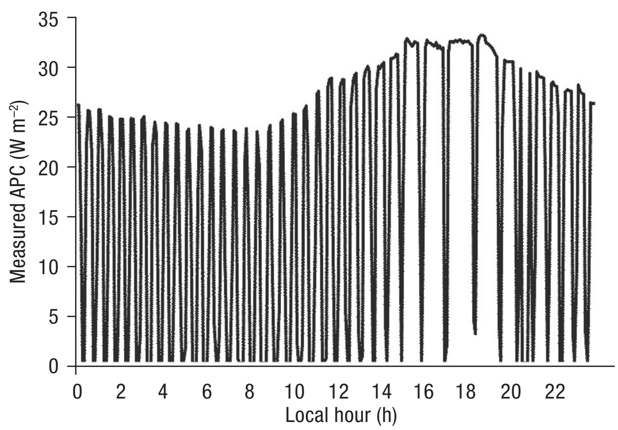

Figure 7. Actual Power Consumption (APC, W m^{-2}) measured over a typical day.

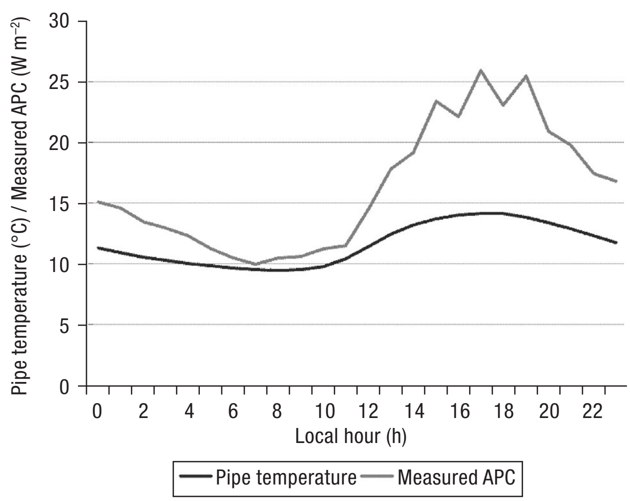

Figure 8. Pipe temperature (°C) and measured APC (W m^{-2}) for an average day calculated from the data collected over 5 days.

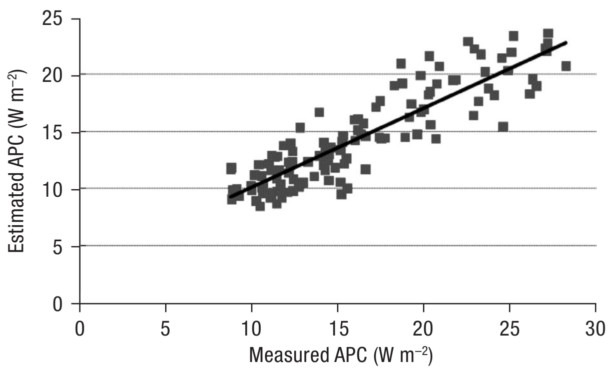

Figure 9. Validation of the heat pump model ($r^2 = 0.78$, n = 120). Estimated APC *vs.* measured APC. Mean values for 5 days of the summer of 2006. Rated power consumption, 34.1 W m^{-2}.

the measured (calculated from the data recorded by the electrical power analyzer) and estimated APC. Based on the performance curves in the *Hawaii Energy Code Application Manual*, Eq. [2] allowed the estimated APC to be calculated with a coefficient of determination (r^2) of 0.78 with respect to the measured APC. Nonetheless, this expression, which makes use of six coefficients, can be simplified to an equation based solely on the outside air temperature (T_o; validation temperature range: 40.3°C to 15.5°C) and the greenhouse wet bulb temperature (T_{wb}, validation temperature range: 23.48°C to 6.23°C):

$$APC(estimated) = $$
$$= RPC(-0.361 - 0.098T_{wb} + 0.081T_o) \quad [2]$$
$$r^2 = 0.78, \quad n = 120$$

This provides practically the same results and it is a useful and simpler model for growers to calculate the power consumption provided T_o (°C) and T_{wb} (°C).

In summary, these calculations allowed the power demand of the heat pump to be determined from the T_o and T_{wb} each hour, which provided an economic assessment of the RHF system when used in cooling mode.

The model enabled another comparison of the RHF system and different cooling strategies, this time under different outside climate conditions. In regions where maximum air temperatures are not very high, shading (or similar systems, *i.e.* whitening) could be enough to meet the cooling needs; in climates with higher cooling needs it would be necessary to choose between evaporative systems and heat pumps (RHF or similar). Regarding the RHF systems, this study showed the increase in energy consumption as a function of the outside air temperature with an estimated value of 13.8 Wh m^{-2} d^{-1} per °C (calculated with Eq. [2]). This increase involves an important cost rise, so evaporative cooling systems (such as fogging) would be preferable to the RHF system in dry climates. In humid climates the efficiency of evaporative cooling systems are not so high and the RHF system can be competitive. Therefore, hot and humid climates seem to be the most suitable climates for the use of the RHF or other systems based on heat pumps.

Conclusions

The cooling effect of the RHF system was only significant up to a height of 0.5 m above the floor, at which a reduction of approximately 1°C was achieved compared to that obtained in the control scenario. No significant effect was seen at 1.5 m.

The results show the effect of the RHF system to be very limited. In contrast, fogging systems can reduce the temperature of the entire greenhouse by 4°C under the climate conditions of Madrid.

The heat pump performance model developed was able to predict the power demand of the heat pump from the outside air temperature and the greenhouse wet bulb temperature.

Acknowledgments

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