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Shading screens for the improvement of the night-time climate of unheated greenhouses

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Abstract

The objective of this work was to study the effect of shading screens, normally used during the day for cooling purposes, on the night-time climate of unheated greenhouses. For this purpose, first a number of experimental measurements were taken during cold nights to characterise the greenhouse climate both with and without an aluminised external screen. Secondly a Computational Fluid Dynamic (CFD) model of greenhouse was developed. After validation of the model by comparison with experimental data, the model was used to simulate the greenhouse climate for different sky conditions ranging from cloudless to overcast nights. Simulations were performed for a greenhouse with internal and external shading screens and for the same greenhouse without screens. Experimental results showed the positive effect of an external shading screen, whose use increased night-time temperature and reduced the risk of thermal inversion. Its effect was much stronger under clear sky conditions. The CFD model supported this conclusion and provided a detailed explanation of the temperature behaviour of all the greenhouse types considered. CFD simulations proved that an aluminised screen placed inside the greenhouse at gutter height gave the greatest thermal increase. Therefore, external or internal screens can help to increase the sustainability of greenhouse production in areas with mild winter climates by enhancing the use of solar energy stored in the greenhouse soil during the previous day and released at night-time.

Additional key words: CFD model; movable shading; roof temperature; thermal inversion.

Introduction

In periods of high radiation, greenhouse crops in warm climate areas suffer from high temperatures and notable vapour pressure deficits: these have negative consequences for crop growth, development and quality. To control such negative conditions a number of cooling methods such as ventilation, evaporative cooling or shading are commonly used (Boulard & Baille, 1993). Reducing the solar energy transmission into the greenhouse by shading improves thermal and hygrometric conditions, but it can also lead to an important reduction in incident radiation reaching crops which in turn would represent less photosynthetic assimilation and consequently less production (Lorenzo *et al.*, 1997). Dynamic shadowing systems that only reduce radiation at certain times of the day, when conditions are most stressful, result in smaller reductions in yield than in the intercepted radiation (De Koning, 1988, as reported by Stanghellini, 1994). Lorenzo *et al.* (2003, 2004) pointed out the benefits of using external greenhouse mobile shading to control climate conditions in Mediterranean greenhouses during hot periods and highlighted its positive effect on fruit quality, as physiological disorders

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Abbreviations used: BER (blossom end root); CFD (computational fluid dynamics); GES (greenhouse with external screen); GIS (greenhouse with a horizontal internal screen); GNS (greenhouse with no screen); PE (polyethylene).

Nomenclature: C_p (specific heat of air, J kg^{-1} K^{-1}); h (heat transfer coefficient from the leaf, W m^{-2} K^{-1}); l(the characteristic length of the leaf, cm); N (net radiation from the leaf, W m^{-2}); T_i (greenhouse air temperature, K); T_l (leaf temperature, K); T_o (outdoors air temperature, K); T_{sky} (sky temperature, K); u (air velocity around the leaf, cm s^{-1}); ρ (air density, kg m^{-3}).

such as BER (blossom end root) were reduced. In addition, shading diminishes canopy transpiration as well as water uptake by crops, thus improving the efficiency of water use.

Screens of different types have long been used in heated greenhouses for the purpose of energy conservation. Bailey (1981) concluded that a screen with a low-emissivity upper surface and high-emissivity lower surface gave the highest energy savings. Kittas *et al.* (2003) showed that a thermal screen induced a more homogeneous microclimate and produced a considerable energy saving.

Much less is known about the effect of screens in unheated greenhouses. Shading screens can also be effective in reducing the risk of frost damage (Teitel & Segal, 1995; Teitel *et al.*, 1996) and eliminating the problem of thermal inversion. These problems occur on clear nights when a large amount of radiant heat is sent back to the sky. As a consequence, greenhouse air is not only cooler than required, but there is also a higher risk of dew forming and dripping over the crop. Therefore, any means of increasing the night-time temperature regime is of great importance, particularly if this is achieved by passive means without external heating (Montero *et al.,* 1986; López, 2003). Research conducted by Teitel *et al.* (1996) found that shading screens stretched horizontally over the crops acted as a barrier to thermal radiation and had positive repercussions for air and leaf temperatures under the screen. Aluminised screens proved to be more effective than either black or white screens. Teitel *et al.* (1996) suggested using screens only when frost damage was expected so as not to reduce the amount of light available during the day: this is possible when using dynamic or movable shading. Teitel's study was based on a very simple shelter formed by a woven screen in an open field. We are not aware of any similar study based on a plastic screened greenhouse.

Computational fluid dynamics (CFD) can be used to analyse the effect of shading on the night-time greenhouse climate. CFD has recently become a widely available and efficient research tool for studying greenhouse climate. It offers many advantages with respect to other methods, including the ability to provide very detailed information about temperature distribution and velocity fields, etc., at any point within the computational domain. Reichrath & Davies (2002) presented a comprehensive review of the main applications of CFD for the study of greenhouse behaviour. Most CFD early studies have been based on natural ventilation (Mistriotis *et al.*, 1997; Brugger *et al.*, 2003; Molina-Aiz *et al.*, 2004) Later on CFD applications have considered energy equations and temperature maps (Kacira *et al.*, 1998; Fatnassi *et al.*, 2003; among others). CFD has also been used for the design of more efficient ventilation systems. For instance Kacira *et al.* (2004) and Baeza *et al.* (2009) conducted CFD simulations to investigate the effect of side vents in relation to the number of spans. Both studies showed the importance of side ventilation combined with roof ventilation in large greenhouses. Other aspects such as the effect of the roof slope, ventilator size and internal deflectors on ventilation rate and climate uniformity have been considered by Baeza (2007). The effect of insect-proof screens on ventilation has also been analyzed in recent CFD studies (Teitel, 2010).

As pointed out by Bournet & Boulard (2010) on a review paper about greenhouse ventilation, until now only a few studies have included radiative mechanisms by solving the radiative transfer equation (Lee & Short, 1998; Montero *et al.*, 2005; Bournet *et al.,* 2006, 2007; Kim *et al.*, 2008). In passive greenhouses, particularly at night, far infrared radiation exchange controls the heat loses from the greenhouse (Baille *et al.*, 2006). But very few CFD studies have included detailed analysis of cover energy fluxes that involve the interchange of long wave infrared radiation between the sky and the greenhouse cladding (Iglesias, 2005; Montero *et al.*, 2005).

The objective of this work was to study the effect of shading screens, which are normally used during the day for cooling purposes, on the night-time climate of unheated greenhouses.

Material and methods

The experimental greenhouse

The experiment was carried out in a 720 m^2 experimental multispan greenhouse covered with a 0.2 mm thermal polyethylene (PE) plastic film; its emissivity, transmissivity and reflectivity for far infrared radiation were 0.69, 0.19 and 0.12, respectively and the thermal conductance was 0.3 W m^{-1} K^{-1} (manufacturer's data). The greenhouse was located at *Instituto de Investigación y Formación Agraria y Pesquera* (IFAPA, Almería, Spain, 36° 50' N, 2° 18' W). The curved-roof structure had three spans of 30 × 8 m, an E-W orientation, and a maximum height of 4.7 m, with a height of 3 m under the gutters. The greenhouse had no crop since this study was focussed on the night time energy balances and humidity balance was not included in this study. A 10-cm thick sand mulch covered the greenhouse soil, which is a common practise in the area.

A metallic structure over the greenhouse supported an external greenhouse mobile shading system with an aluminium screen (Ludwig-Svenson OLS 50) which was 1.3 m above the top of the roof and 3 m above the gutter. According to the manufacturer the emissivity and transmissivity for far infrared radiation were 0.21 and 0.42 respectively, reflectivity accounting for the balance to 1. The screen thermal conductance was taken the same as that of the PE film since no data from the manufacturer were available. The screen could be extended or folded automatically. In order to study the possible use of this type of screen on cold nights, we evaluated its influence on greenhouse energy fluxes and temperature at night (between 22:00 and 6:00, solar time), comparing greenhouse conditions both with and without the screen.

Measurements were taken under different wind conditions and on still nights, with cloud cover ranging from clear skies to overcast conditions. Nights with partial cloud cover were also considered in the study. Measurements were always taken in winter or early spring (mostly in 2005) to analyse the effect of the screen during the coolest months in the area. During measuring periods all ventilators were kept shut. Net radiation was measured inside the greenhouse ($Rn_{,i}$) and below the outside screen ($Rn_{,o}$) using radiation balance probes (model 8110) by Philipp Schenk (Wien, Austria). Air temperature was recorded usingT-type (copper-constantan) thermocouples located both inside (T_i) and outside (T_o) the greenhouse. Plastic temperature (T_p) was measured by two thermocouples (provided with a surface measuring device/adaptor) located on the down side of the plastic. Heat transfer from the ground (q) was measured by two heat flux sensors (HFS-4, Omega Engineering Inc., Stamford, CT, USA) placed on the ground surface in the centre of the greenhouse.

Since the thermal radiation exchange between the greenhouse and sky was expected to have a dominant role on greenhouse cooling at night, it was decided to relate greenhouse temperature to the equivalent black-body sky temperature (T_{sky}) (Duffie & Beckman, 1980). To determine T_{sky}, a radiation balance probe (model 8110) by Philipp Schenk was placed 0.5 m above a 1 m wide by 1.5 m long sheet of glass. The upper surface glass temperature was measured by a T-type surface temperature sensor. Assuming an emissivity of 0.94 for the glass (ASHRAE, 1989) and knowing its temperature, the Stephan-Boltzmann law allowed us to calculate the amount of energy emitted from the glass, and with this value and the reading from the net radiometer, it was possible to estimate the amount of energy emitted from the sky. The Stephan-Boltzmann law therefore provided T_{sky} according to a similar procedure to that used by Bot (1983).

Fig. 1 shows the sensor location in a schematic plan of the greenhouse. Data were sampled every minute by a CR23X Campbell micrologger (Logan, USA) and averaged over 5-min intervals. Outside the greenhouse, wind speed and relative humidity were measured by a weather station (DGT-Volmatic, Soendersoe, Denmark) and computer. Data were stored every 5 minutes.

The CFD model

The simulated greenhouse was a replica of the experimental greenhouse. A two-dimensional steady-state

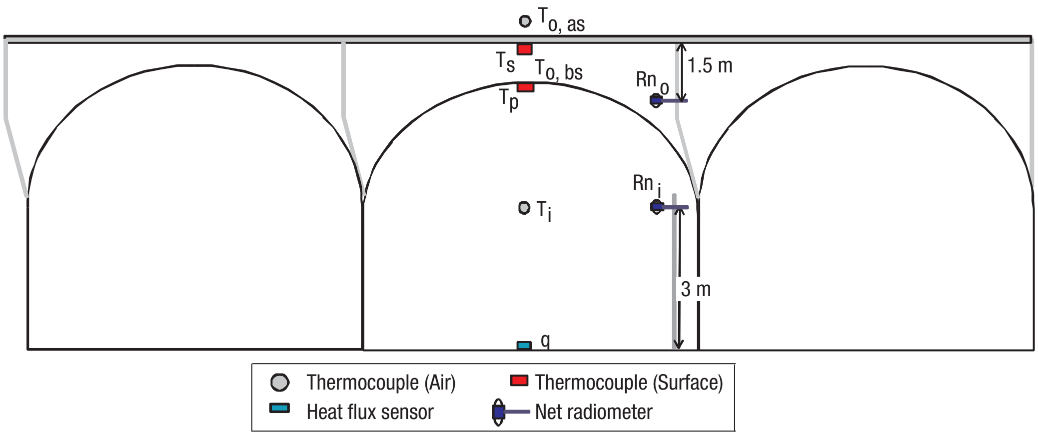

Figure 1. Schematic plan of the experimental greenhouse and sensors.

CFD model was developed using FLUENT 6.1 software. The model represented a cross section through the centre of the three-span greenhouse. It was located within a computational domain 60 m long and 30 m high. The leading edge of the greenhouse was located 20 m downwind of the velocity inlet.

For the first set of simulations, the cladding was a single layer of polyethylene (PE with a thickness of 0.2 mm and the same radiative properties and thermal conductance as that of the experimental greenhouse film). This greenhouse was called GNS (Greenhouse with No Screen). Care was taken when meshing the cladding to ensure that the finite elements to which the Navier-Stokes equations were applied were 0.1 mm wide. Finite elements of this size made it possible to monitor temperature and energy fluxes on both sides of the cladding. A second set of simulations were run for a greenhouse with the same dimensions but with a 0.2 mm thick external aluminised screen; the optical and thermal properties were the same as that of the experimental screen. Screen porosity was taken as zero, so no air flow occurred through the external screen. This greenhouse was called GES (greenhouse with external screen). A meshing scheme similar to that used for the first set of simulations was used for the PE cladding and the aluminised screen. Finally, a third set of simulations were run for a greenhouse with a horizontal internal screen (GIS). The optical and thermal properties of the internal screen were the same as the external screen. No airflow through the internal screen was assumed.

In order to account for gravity forces due to air density (temperature) changes, the Boussinesq hypothesis was used for the whole of the computational domain (Baeza *et al.*, 2009). This method treats density as a constant value in all the solved equations, except for the gravity term (thermal effect) of the momentum equation:

$$(\rho - \rho_r)g \approx \rho_0 \beta (T - Tr)\, g \qquad [1]$$

where the subscript defines a reference state. The Boussinesq approach is valid if the density (temperature) gradients occurring in the computational domain are not too large; that is, if $\beta(T - T_r) << 1$. In our case, with a naturally ventilated greenhouse, the temperature differences are never very large (< 20°C). Therefore, the Boussinesq simplification can be applied. Using this approach, a better convergence in natural convection problems is achieved compared with treating density as a function of temperature. The CFD model included a radiation sub-model that allowed calculations of radiative heat transfer between the different surfaces of the domain. For this purpose, a discrete ordinate radiation model was used (Fluent Inc, Paris, France). This model required the optical properties of the cladding. For the 0.2-mm thick PE film and aluminised screen the real properties of the experimental greenhouse mentioned before were used for calculations.

A domain temperature of 283 K was chosen as the boundary condition for air temperature, since average night-time temperatures during the coldest months in the Mediterranean are normally close to this value (Montero *et al.*, 1985). Soil temperature outside the greenhouse was also taken as 283 K, while heat transfer from the greenhouse soil to the air was taken as a constant 20 W m^{-2} for the simulations, which was confirmed by experimental data reported later. For the sake of simplicity, a constant wind speed of 1 m s^{-1} was applied for all simulations. This simplification was introduced because the main objective of this study was to model thermal radiation cooling and to compare greenhouse climate under different sky conditions. Furthermore, low night wind speeds prevail in most Mediterranean climates at night.

To choose a suitable range of equivalent sky temperatures (in terms of radiation exchange) for the simulations, some expressions cited in literature were used. For clear skies, Swinwank (1963) proposed a simple relationship that relates sky temperature (T_{sky}) with air temperature T_o (both expressed in K) by:

$$T_{sky} = 0.0552\, T_o^{1.5} \qquad [2]$$

The average minimum night time temperature during the coldest months in Almería is close to 283K (Montero *et al.*, 1985). From Eq. [2], if T_o is taken as 283 K then T_{sky} is 262.8 K. Other expressions (*e.g.* Bliss, 1961; Berdahl & Martin, 1984) take into consideration the dew point temperature. According to Bliss (1961), for a clear night with high humidity, T_{sky} can be around 10 K cooler than T_o. For overcast nights, cloud cover tends to increase sky temperature. Simulations were therefore run for sky temperatures of 263 K to represent clear nights with low humidity, 273 K for clear nights with high humidity, and 283 K for completely overcast nights.

Although the model is complex, some simplifications had to be accepted, mainly in order to reduce the computational effort:

— The influence of internal and external humidity was not considered. Once initial values for internal and external humidity were chosen, no humidity sink or sources were taken into consideration and so no condensation rate was calculated.

— Infiltration losses were taken as zero, due to the difficulty of modelling leakage. This assumption was accepted because in the case of passive greenhouses the difference in temperature between internal and external air is small, and therefore infiltration heat losses are not as important as for heated greenhouses.

Results and discussion

Experimental results

Night-time temperature evolution

Fig. 2 shows the night-time evolution of the outside air and greenhouse air temperatures for GES and GNS. Results are presented for two clear nights in winter (Fig. 2a) and spring 2003 (Fig. 2b) with different outside air temperatures.The equivalent sky temperature ranged from 255 to 259 K (night 28-29 January), 260 to 264 K (night 30-31 January), 274 to 276 K (night 23-24 April) and 272 to 275 K (night 24-25 April). Greenhouse cover temperature was added in Fig. 2b, but these data were not available in Fig. 2a. For GNS, a thermal inversion was observed, with the greenhouse air being around 2 K cooler than that outside on the coolest night and around 1 K cooler for nights in spring. On the contrary, with the external screen (GES), greenhouse air temperature was similar to or slightly higher than that of the external air.

For the second period (Fig. 2b), roof temperature also showed the effect of the screen. Without the screen, roof temperature was up to 3 K cooler than greenhouse air, while with the screen, the roof temperature was very similar to that of the outside air. The external screen therefore had a positive effect on the thermal regime. These differences in temperature may not seem particularly remarkable, but for unheated greenhouses in which many night-time temperatures are below the biological optimums for most crops (Tognoni, 1990), they have clear practical advantages such as promoting better growth, protecting against frost damage and reducing the risk of condensation dripping.

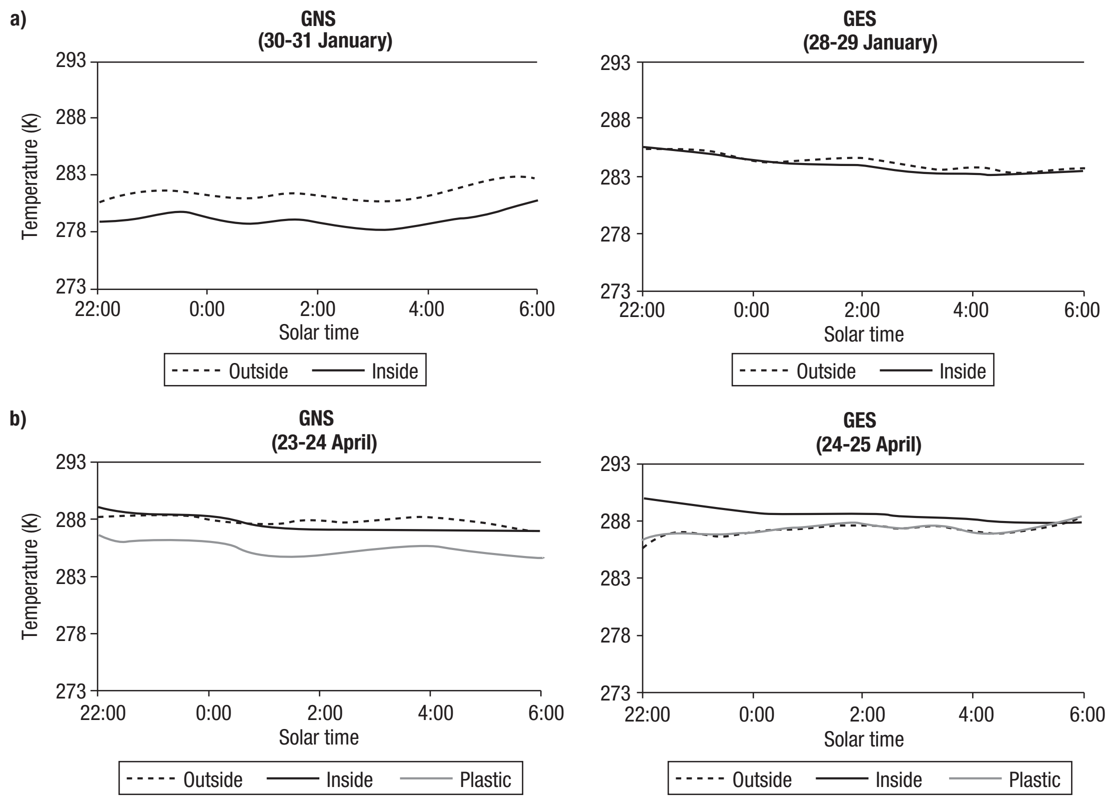

Figure 2. Outside air, greenhouse air and plastic film night-time temperature evolution for greenhouse with external screen (GES) and without screen (GNS).

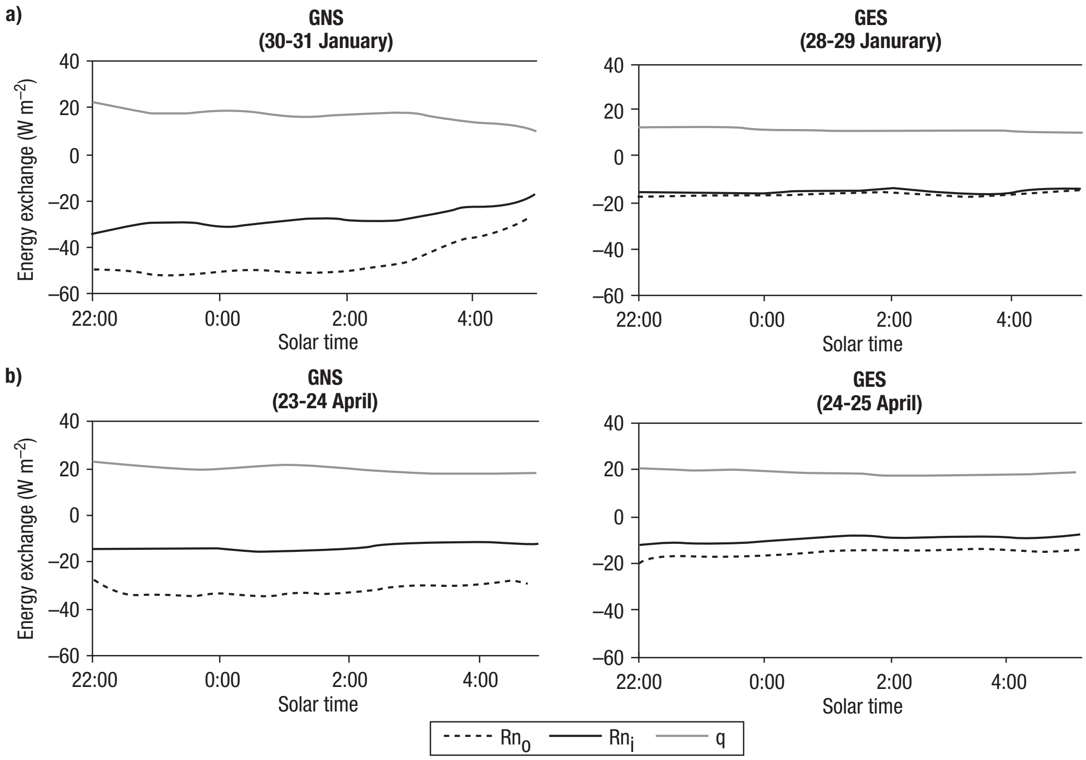

Figure 3. Night-time evolution of net radiation inside (Rn_i) and over greenhouse (Rn_o) with no screen (GNS) and greenhouse with external screen (GES) plus heat flux from soil surface (q) to greenhouse air for GNS and GES.

Night-time energy fluxes measured experimentally

Fig. 3 shows the net radiation both over the greenhouse and below the screen (when it was extended), Rn_o, and inside the greenhouse, Rn_i. The heat flux from the soil to the greenhouse air (q) is also presented. Energy fluxes are illustrated for both conditions, with and without the external screen, and for two different clear nights. For the greenhouse without a screen (GNS), absolute values of Rn_o were greater than the heat flux from the soil. This means that the greenhouse cover lost more heat by thermal radiation that it received from inside the greenhouse. To make the energy balance hold true under steady-state conditions, it seemed that the cover was heated by convection from external air, because the temperature of the plastic was lower than that of the external air. For GNS, Rn_i was lower in absolute terms than Rn_o, due to the fact that the emission of thermal radiation from the clear sky was smaller than the emission from the internal side of the cover.

This was not the case of the greenhouse with the external screen (GES). For both GNS and GES, the heat flux from the soil was steady and near 20 Wm^{-2} but an important reduction in Rn_o was observed due to the screen. It seems that the screen isolated the greenhouse from the radiative conditions of the clear sky. As a result, for the same energy input from the soil, radiation losses were smaller and air and cover greenhouse temperatures were higher.

Greenhouse air temperature as a function of sky and outside air temperature

Since radiative cooling was responsible for the main differences in climate between GNS and GES, it was decided to investigate the influence of sky temperature on greenhouse air temperature. For very clear nights, sky temperature was as much as 20 K below ambient air. Under these conditions, a maximum thermal inversion of 2.6 K was measured in GNS (Fig. 4a). Thermal inversions close to this value had been previously recorded in the same area (López, 2003). As sky temperature increased, so did greenhouse air temperature. For overcast nights, sky temperature was higher than for clear nights (up to 6 K below ambient air) and the temperature of greenhouse air was higher than that of the outside air. There was a good linear relationship (Fig. 4a) between T_i-T_o and T_{sky}-T_o with

$$T_i - T_o = 0.28\,(T_{sky} - T_o) + 3.33\ (R^2 = 0.84) \qquad [3]$$

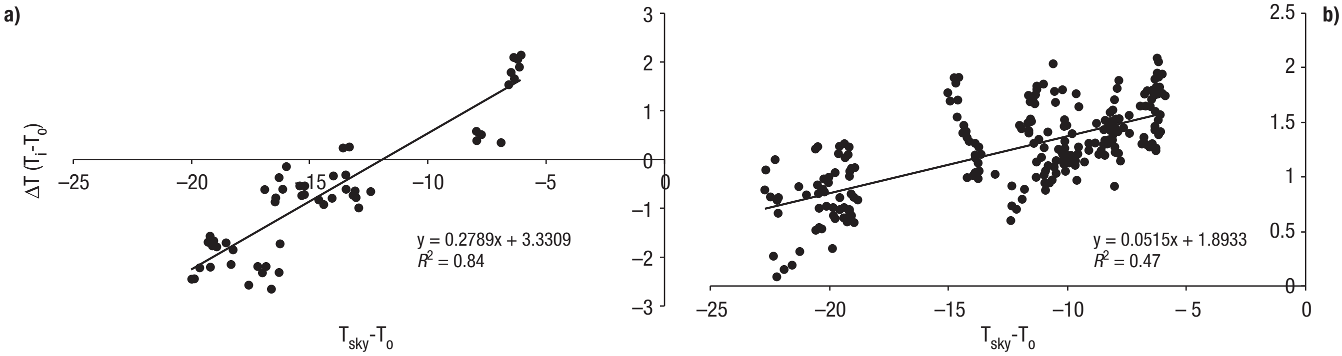

Figure 4. Regressions from experimental data between T_{sky}-T_o and T_i-T_o for greenhouses with (a) no screen (GNS) and (b) with external screen (GES).

For GES, the linear relationship between these same variables was not so good (Fig. 4b). Regression analysis yielded:

$$T_i - T_o = 0.05\ (T_{sky} - T_o) + 1.89\ (R^2 = 0.47) \quad [4]$$

The slopes of Eqs. [3] and [4] account for most of the radiative exchange, so that when T_{sky} equals T_0 the exchange of thermal radiation is small (there is still some radiative exchange since the cover temperature T_c can be different to T_o); therefore the fact that the slope in Eq. [3] is higher than in Eq. [4] shows that the screen isolated the greenhouse from the radiative conditions of the clear sky as it has been mentioned before.

The intercept of Eqs. [3] and [4] accounts for most of the convective exchange between the greenhouse and the outside air, so that in the absence of thermal radiation exchange the difference between interior and exterior temperature ($T_i - T_o$) is due to convection. The intercepts in Eqs. [3] and [4] are different; it can be that either the convective heat transfer coefficient for both greenhouses was different or the experimental conditions were different (more wind for the GNS data). Nevertheless other studies have shown that the convective heat transfer coefficient with and without external screen was nearly the same (about 6 W m^{-2} K: Piscia *et al.*, 2012). Moreover no relevant differences were found on the wind regime during the measurement for GNS and GES.

The reason for the poorer fit and different intercept for GES could be the low dependence of $T_i - T_o$ on sky temperature as shown by the reduced slope of the regression line in Eq. [4] any minor error in the measurement of T_i or T_o could have increased the dispersion of the experimental points around the regression line. According to Fig. 4b no thermal inversion was observed in GES, even on the clearest nights for which ($T_{sky} - T_o$) was less than –20 K. It is interesting to observe that for overcast nights ($T_{sky} - T_o$ close to –5 K) the increase in temperature in the greenhouse with reference to the outside air was nearly the same for both the screened and the unscreened greenhouses. This confirmed that the main effect of the external screen at night was to reduce thermal radiation losses, which were less important in overcast nights.

Results from CFD simulations

Greenhouse with no screen (GNS)

The temperature contour of the central area of greenhouse GNS —assuming the sky to be acting as a black body with a temperature of 263 K (20 K lower than room temperature)— is shown in Fig. 5. The colour range specifies the zones with lower temperatures in blue and higher temperatures in red.

The thermal performance in the simulated greenhouse was similar to the characteristics observed in the experimental greenhouse. As seen in Fig. 5, the floor acted as the heat source as it was the zone with the highest temperature, whilst the roof was the energy sink due to its high thermal radiation.

Therefore the temperature of the whole roof was 3.5 K lower than that of the external air and 1.6 K lower than that of the air in the greenhouse. These features are presented in Tables 1 and 2, which also show an abstract of the results obtained by the simulations with CFD models for different roof types that will be commented later on. As seen in Table 2, nocturnal net radiation for GNS was –32.07 W m^{-2}, whilst internal net radiation was around –15.59 W m^{-2}. The temperature and net radiation features reveal that the greenhouse was heated by convection from the warmer outside air, as suggested by the aforementioned experimental results.

Figure 5. Temperature (K) contour for central span of greenhouse with no screen (GNS) for clear sky conditions.

Figs. 6a,b,c show thermal maps for the greenhouse without a screen (GNS) under three different situations: i) a cloudless sky on a dry night (temperature of 263 K), ii) a cloudless sky on a humid night (temperature of 273 K) and iii) a completely overcast sky (temperature of 283 K) relating to the previously mentioned sky temperatures. The most characteristic feature to point out is perhaps the pronounced thermal inversion of 2.5 K for $T_{sky} = 263$ K. A similar inversion has also been reported for several previous studies based on greenhouses without heating (Montero *et al.*, 1986; López, 2003).

Table 1. Increase in temperature (K) associated with an external air temperature of 283 K for the three greenhouse types under consideration and for three equivalent sky temperatures (K) taking the sky as a black body

Greenhouse type	Equivalent sky temperature	Increase in temperature		
		Greenhouse air	Greenhouse roof	Screen
No screen (GNS)	263	–1.6	–3.5	—
	273	+0.8	–0.9	—
	283	+3.3	+1.8	—
With external screen (GES)	263	+2.1	+0.5	–2.8
	273	+2.7	+1.2	–1.2
	283	+3.4	+1.9	+1.4
With internal screen (GIS)	263	+1.8	–3.8	–0.1
	273	+3.6	–1.2	+2.2
	283	+6.0	+1.6	+4.7

On completely overcast nights, no thermal inversion was observed and the greenhouse temperature was 3.6 K higher than the external temperature. It should not be forgotten that the simulated greenhouse was completely air tight, so in a real greenhouse the thermal variations would not be so pronounced.

It was observed that as sky temperature rose from 263 K to 273 K and 283 K the net radiation to the greenhouse changed from –32.07 to –20.28 and –8.11 W m^{-2}, respectively, which had an effect on the roof temperature. Therefore, for the single clad greenhouse, the roof temperature was at 3.5 K lower than the outside air on clear dry nights, whilst on cloudy nights the roof temperature was 1.8 K greater than the outside temperature (Table 1). This confirmed observations suggesting that condensation is higher on clear nights as a consequence of the greenhouse roof cover being colder in clear sky conditions.

Greenhouse with external screen (GES)

Figs.7a,b,c show the temperature distribution for the greenhouse with an external screen (GES) under the three situations considered. The influence of the external screen was significant. For all cases of sky temperature, the greenhouse air was warmer than the outside air. According to the simulations, the screen could help to increase air temperature by around 3.7 K on clear nights with respect to the single clad greenhouse. As

Table 2. Energy fluxes for the three greenhouse types under consideration and for three equivalent sky temperatures taking the sky as a black body

Greenhouse type	Equivalent sky temperature (K)	Roof: Total heat loss (Wm^{-2})	Roof: Net radiation above greenhouse (Wm^{-2})	Roof: Net radiation inside the greenhouse (Wm^{-2})	Side walls: Total heat loss (Wm^{-2})
No screen (GNS)	263	18.54	–32.07	–15.59	–2.30
	273	17.01	–20.28	–14.43	4.31
	283	15.43	–8.11	–13.15	11.48
With external screen (GES)	263	15.83	–13.43	–13.37	9.70
	273	15.53	–10.03	–13.16	10.64
	283	15.35	–6.26	–12.98	11.80
With internal screen (GIS)	263	16.52	–30.94	–15.52	8.19
	273	14.74	–19.50	–14.30	9.35
	283	13.33	–7.10	–12.81	13.22

the sky temperature increased, the positive effect of the screen decreased and on totally overcast nights, greenhouse air temperature was nearly the same for both screened and unscreened greenhouses since, as mentioned before, the convective heat transfer coefficient with and without screen was very similar.

Roof temperature also benefited from the external screen since the roof temperature in GES was up to 4 K higher when T_{sky} was 263 K. Thus, comparing GNS and GES, it is observed that the latter has clear advantage over the former, with the air having a higher temperature, and a lesser dependency on sky conditions.

Besides the simulations already discussed, others were made for sky temperatures of 268 K and 278 K for both greenhouses. With these simulations, thermal behaviour was calculated for a set of five different sky conditions. Regression analysis was then conducted for $(T_i - T_o)$ and $(T_{sky} - T_o)$.

For GNS, this analysis yielded:

$$(T_i - T_o) = 0.25\ (T_{sky} - T_o) + 3.34\ (R^2 = 0.99) \quad [5]$$

Figure 6. Temperature contour in greenhouse with no screen (GNS) for T_{sky} equal to 283 K (a), 273 K (b) and 263 K (c).

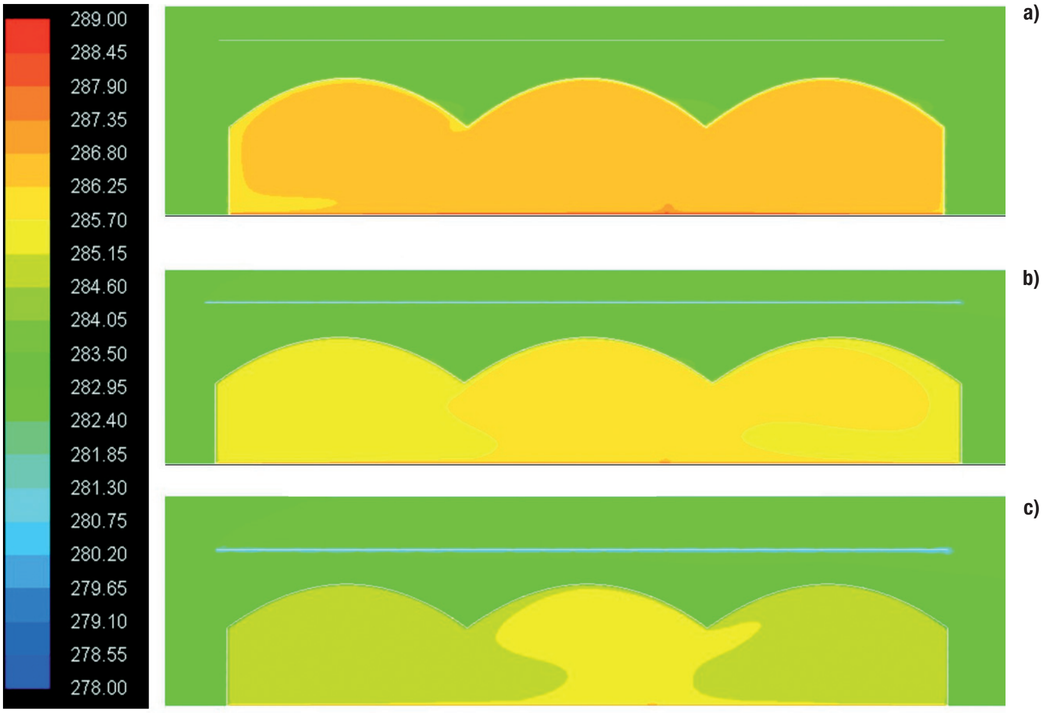

Figure 7. Temperature contour in greenhouse with external screen (GES) for T_{sky} equal to 283 K (a), 273 K (b) and 263 K (c).

And for the screened greenhouse GES, it was:

$$(T_i - T_o) = 0.06\ (T_{sky} - T_o) + 3.39\ (R^2 = 0.99) \quad [6]$$

Eqs. [3] and [5] are similar since the intercepts and slopes of the two regressions are similar. The slope of Eq. [4] is also similar to that of Eq. [6]. It should be added that, in spite of the simplifications assumed in this study, the CFD model largely confirmed measurements relating to the real greenhouse. Not only did the model show a similar response for greenhouse air temperature as for sky temperature, but the roof temperature pattern and net radiation values were also similar for both the experimental and simulated data sets. It seems that the CFD model was good at explaining the thermal behaviour of the greenhouse under a number of external boundary conditions and provided much more detailed information than can be obtained from measurements. We therefore conclude that it would also be possible to use the CFD model to investigate other aspects or other case studies that are discussed below.

Greenhouse with internal screen (GIS)

Figs. 8a,b,c show the temperature contour for GIS (greenhouse with internal screen) under the three situations considered. The temperature contour profile in Fig. 8 shows two clearly differentiated areas. Above the screen three regions at cooler temperature can be observed. Below the screen, it can be seen that the greenhouse air was warmer than the outside air. Compared with GNS, the increase in temperature for GIS was between 3.4 K and 2.6 K depending on the sky conditions. These values are within the range measured in experimental greenhouses with single skin and internal screen in the same area (Montero *et al.*, 1986). Additional simulations were made for sky temperatures of 268 K and 278 K for GIS as with the GES and GNS greenhouses. Regression analysis for the set of five different sky conditions for GIS yielded:

$$(T_i - T_o) = 0.21\ (T_{sky} - T_o) + 5.84\ (R^2 = 0.97) \quad [7]$$

Eq. [7] confirms the increased thermal insulation from the internal screen since its intercept was 5.84 while the intercept for GNS was 3.34 (Eq. [3]). If GES and GIS are compared (Eqs. [6] and [7] and Table 1) it can be seen that GIS had a more pronounced slope than GES, which means that the air temperature for GIS was more dependent on sky conditions. The intercept was also greater since the internal screen created higher night time temperatures than the external screen. An exception to this observation was when T_{sky}

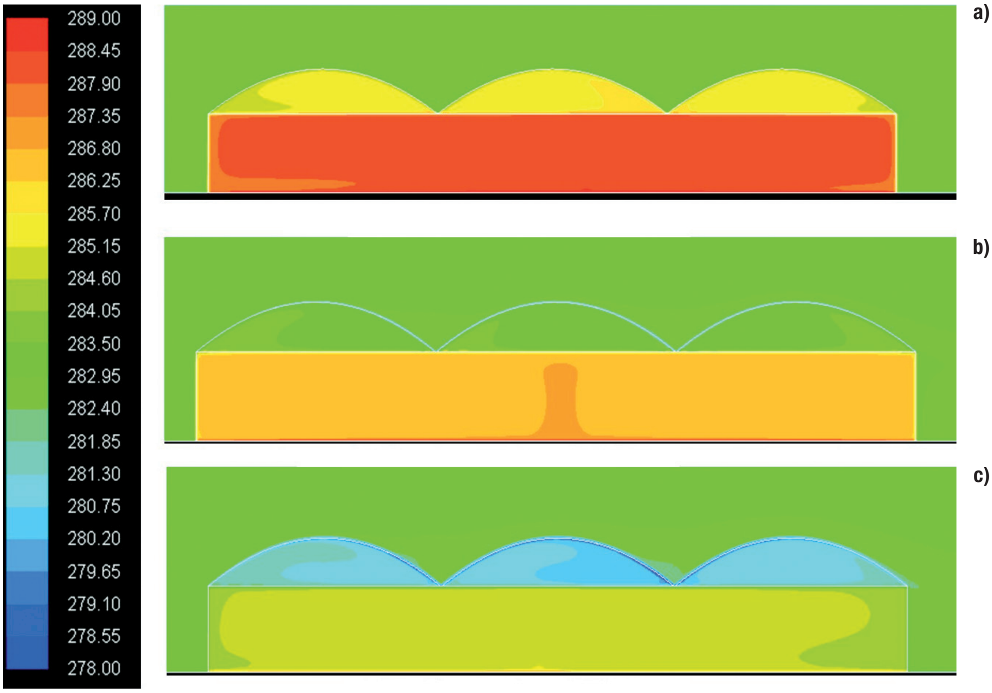

Figure 8. Temperature contour in greenhouse with internal screen (GIS) for T_{sky} equal to 283 K (a), 273 K (b) and 263 K (c).

was 263 K. Perhaps the reason for this exception was that the internal screen created a confined air chamber below the roof mainly due to the emission of thermal radiation from the cover. For very clear sky conditions such chamber was approximately 2 K below the outside air. This cold chamber could cause that air temperature in GIS to be slightly less than in GES for very clear sky conditions and could also explain that the air temperature in GIS was more dependent on sky conditions than in GES.

It is important to mention the relevant increase in air temperature that the airtight curtain produced in the case of the unheated greenhouse. The heat released from the soil could have warmed the greenhouse air temperature to 6 K higher than that of the outside air under very cloudy conditions. This temperature increase is normally greater than what is required in areas with mild winter climates to keep night-time temperatures near optimum values. It also shows that much can be done to improve the thermal conditions of unheated greenhouses at night by making structural modifications to keep the heat collected during the day.

Energy fluxes

Table 2 shows the energy fluxes for the external surface of the cover material for the side walls of the three greenhouse types under three different sky conditions. As previously discussed, thermal radiation is the most relevant process governing the loss of energy. For instance, GNS for T_{sky} 273 K had a thermal radiation loss of 20.28 W m^{-2} which was 119% of the total heat lost through the roof (17.01 W m^{-2}). This means the cover received an average of 3.27 W m^{-2} by convection from the surrounding air (Fig. 9). The heat loss from the external surface was compensated by the heat gains on its internal surface (13.4 W m^{-2} due to thermal radiation plus 3.61 W m^{-2} due to convection from the internal air). While the roof was the energy sink, the soil was the major energy source. The CFD model imposed a constant soil surface heat transfer of 20 W m^{-2} which were transferred by the combination of radiation transfer and convection transfer. In terms of energy

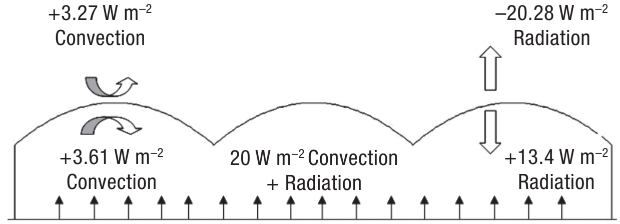

Figure 9. Greenhouse energy balance for the greenhouse without screen (GNS) and T_{sky} 273 K

balance of the whole greenhouse it is important to mention that the roof surface was bigger than the soil surface, so the heat delivered per unit area of the soil surface was higher than the heat lost per unit area from the roof.

For other case studies thermal radiation was not as relevant.This was the case for GES where radiation losses ranged from 41% to 85% of the total loss, with convection losses accounting for the rest.

Energy fluxes from the side walls played an important role in some of the case studies in spite of the fact that the total side wall surface for each metre of greenhouse length was 6 m^2 while the roof surface per unit length was 26.6 m^2. The bigger the increase in temperature of the internal air as opposed to the external air, the greater the importance of the energy fluxes through the side walls. For GIS and T_{sky} 283 K, total heat loss through the side wall was 79.32 W (13.22 × 6). This was 22% of the total loss through the cover (13.33 × 26.6), a percentage that should not be ignored. It seems that for greenhouses with a relatively limited number of spans, an additional increase in temperature could be achieved by increasing the isolation of the side walls.

Airflow pattern in and around the greenhouse

Fig. 10a shows the velocity field in and around GES. Fig. 10b is a more detailed description of the airflow inside GES. Air speed entering the domain was 1 m s^{-1} as in the other simulations already discussed. Perhaps the most notable feature of the velocity field in GES was the fact that the screen accelerated the external air near the upper part of the roof. This may have strong implications for the air pattern and ventilation rate during the day once the roof ventilators are open — a phenomenon that has not been studied in this work but that deserves attention in future research.

The internal airflow pattern (Fig. 10b) showed two circulating cells that helped to maintain uniform temperatures. The movement in the first cell was clockwise and covered the first two spans, while in the second it was anticlockwise. Both cells met near the gutter between the second and third span and created a descending flow from the roof to the floor. Similar pattern was observed in GNS (results not shown for the sake of brevity). Air speed in GNS and GES was close to 0.1 m s^{-1} throughout most of the section, but some stagnation spots were observed in the central areas of the spans.

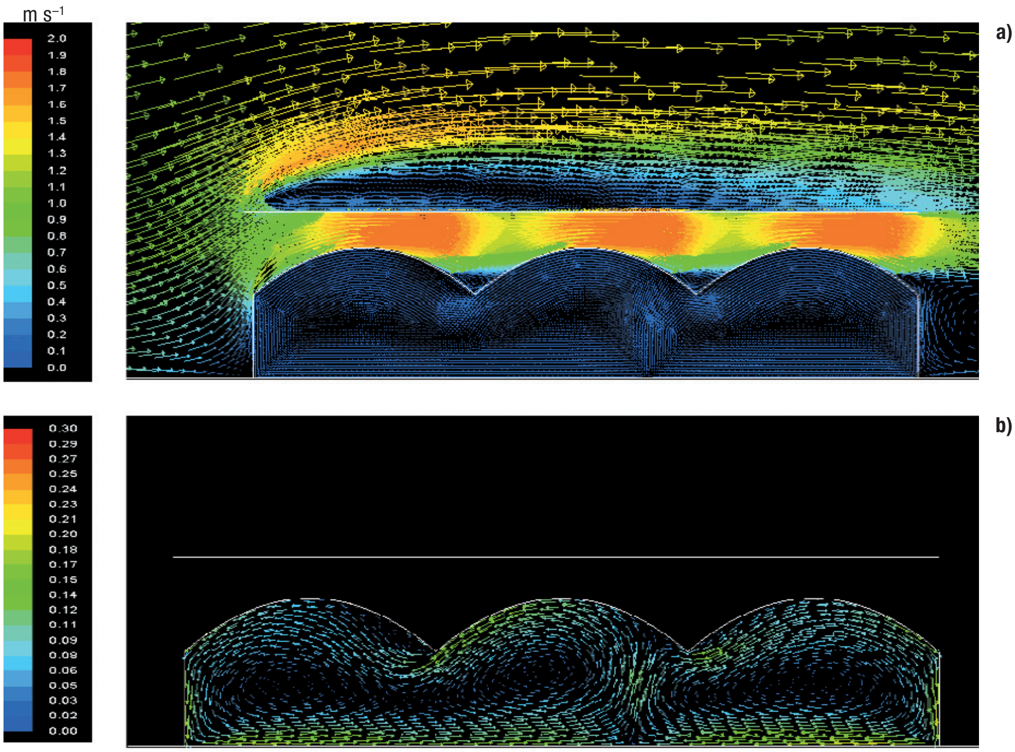

Figure 10. Velocity field (m s^{-1}) in (a) and (b) around GES with a constant external wind speed of 1 m s^{-1}.

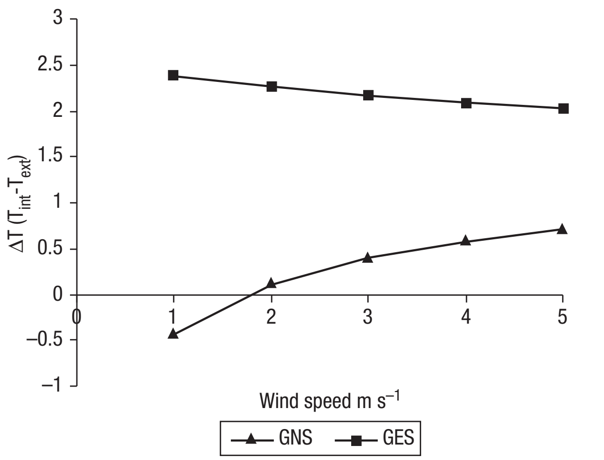

Figure 11. Effect of wind speed on GNS and GES greenhouse air temperatures. $T_{sky} = 268$ K.

Simulations were also performed to study the effect of wind speed on greenhouse air temperature. This is shown in Fig. 11, in which simulations for T_{sky} equal to 268 K and wind speed ranging from 1 to 5 m s^{-1} are presented. It can be seen that increases in air speed had a positive effect on greenhouse air temperature. No thermal inversion was observed for GNS and this was probably due to the fact that the amount of convected heat from the external air increased in line with air speed. Less important wind speed effect was observed for GES since its internal temperature decreased very slowly with wind speed. Table 1 shows that in GES the roof cover temperature is +0.5 K higher than outside air temperature for T_{sky} 263 and + 1.2 K for T_{sky} 273. Since the thermal gradient was low the convection exchange was also low independently of the wind speed.

Concluding remarks

In this work, we have presented a new application for CFD modelling, the study of night-time greenhouse climate. Our main goal was to analyse and compare a number of techniques to improve the control of night-time greenhouse temperature. While the model was intended to be applied for studying thermal improvements to unheated greenhouses, it can also be used to study heated greenhouses, for which detailed information relating to heat transfer mechanisms, heat transfer coefficients etc., can be derived for a range of climate conditions.

Condensation was not considered in this study, mainly due to the difficulty of measuring condensation rate in experimental greenhouses. It is recognised that condensation makes a contribution to the energy fluxes of the roof cover. Nevertheless the magnitude of such contribution is difficult to estimate, since data on this matter from scientific literature are very scarce. Unpublished calculations based on the equilibrium between night time crop transpiration and condensation in unheated Mediterranean greenhouses give energy fluxes due to condensation less than 2 W m^{-2} per unit cover surface, which would be about 10% of the soil heat flux considered in this study. Therefore with the available information condensation would be expected to play a secondary role in the energy balance of the greenhouse.

A movable external screen, normally used for providing shade during the day, proved useful for increasing night-time temperature under clear sky conditions. This conclusion was supported by both experimental measurements and computer modelling. External screens can help to increase the sustainability of greenhouse production in areas with mild winter climates by using the solar energy collected in the greenhouse during the day to enhance night-time temperatures.

In spite of their limitations, the CFD models provided a detailed explanation of thermal behaviour associated with the three greenhouse types considered in the simulations. Not only was the agreement between measured and calculated climate variables satisfactory, but the features shown by all of the CFD models were also physically sound. Logical explanations could therefore be found to discuss the temperature and energy flux patterns.

The results derived from CFD simulations provided a set of regressions for estimating greenhouse air and leaf temperature as a function of equivalent sky temperature (T_{sky}) and outside air temperature (T_o), both of which can easily be measured and calculated.

In unheated greenhouses, the magnitude of the energy fluxes was relatively small, and in most cases the total heat loss and radiation heat loss were less than 20 W m^{-2}. Nevertheless, minor changes in energy fluxes were shown to have a significant practical effect on air and roof cover temperatures. Further simulations are therefore now being conducted to firstly assess the ability of other materials and methods to increase the heat stored and later released from the soil, and to secondly reduce thermal losses from the greenhouse. For the first purpose, a wise election of materials for mulching is a prime consideration: tests conducted in southern Spain concluded that sand mulch such as the one used in the experimental greenhouse was more efficient than any of the plastic mulches analysed in the study by Escobar (2004). For the second purpose, further simulations have shown the potential of using highly reflective aluminised materials on greenhouse curtains: these are able to help increase air temperature by up to 8 K (Montero *et al.*, 2005), although it is also true that the use of highly reflective materials may not be economically interesting in passive greenhouses. Ways of reducing thermal losses through the side walls is also currently being investigated with the help of more complex CFD models incorporating the effect of humidity and infiltration losses.

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