Numerical Simulations of Temperatures in Greenhouse covered with NIR-Reflecting Photoselective Film

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Abstract

In tropical and subtropical areas, greenhouse cultivation is limited by the excess temperatures occurring most of the year due to high radiation levels entering the greenhouse. Under such situations, different cooling methods must be used together in order to maintain the desired temperatures. The most common cooling methods are natural ventilation and shading (generally whitening of the greenhouse cover). NIR-reflecting plastic films are a good alternative to traditional shading techniques. Different types of materials are under development nowadays, but the experimental testing of such materials in different locations, with different climate conditions is expensive in both money and time. Numerical simulations can be a good tool to perform an early evaluation of different sets of photoselective films which differ mainly in their optical properties, selecting the most promising films for later field evaluation. In the present work, a photoselective (NIR blocking) polyethylene film and a standard PE film were tested as covering materials in two adjacent non ventilated boxes and the experimental results of ambient and black body temperature compared with CFD transient simulations. Later, two experimental multitunnel greenhouses were covered with the same materials, and CFD simulations were performed for both greenhouses, and temperatures compared with the experimental measurements for different days, with different boundary conditions, finding a good agreement. Thus proving CFD to be an accurate tool to estimate effects on greenhouse temperatures of greenhouse coverings with different optical properties.

INTRODUCTION

Protected cultivation in tropical and sub-tropical areas of the world is becoming more and more important in the recent years. The majority of these areas are characterized by heavy seasonal rainfalls, which limit the yield and quality of many horticultural crops. Insect infestations are also an important limiting factor. Thus, greenhouse cultivation becomes the best option to achieve high valuable crops in these areas. However, the high levels of solar irradiation all along the year cause an important heat load to accumulate inside the greenhouse, with prevalence of high temperatures and high humidity levels. These values are above the values for optimal growth and development of many crops.

The greenhouses in these areas must be properly cooled to overcome all this problems. Evaporative cooling is not a good option since relative humidity levels are usually high in most of the tropical areas. Natural ventilation becomes the most simple and cheap method to allow the exchange of very hot and humid air from inside the greenhouse with the outside air. The need for insect screening forces the design of large open areas in tropical greenhouses and to make a very efficient use of the combination of side and roof vents (Kamaruddin, 2000; Connelan, 2002; Campen, 2005; Harmanto et al., 2006; Impron et al., 2007). However, natural ventilation itself is often insufficient to cool the greenhouse in these areas. The use of some kind of shading technique (whitening or shading screen) would complement natural ventilation, helping to reduce the high thermal load inside the greenhouse, but its use should be continuous, thus reducing unnecessarily the amount of PAR radiation integral reaching the canopy and therefore, its photosynthesis and final yield. The recent development of NIR-filtering (reflecting or absorbing) greenhouse covering materials and /or coatings (Hoffmann & Waaijenberg, 2002; Hemming et al., 2006; García-Alonso et al., 2006; Sonneveld et al., 2006; Impron et al., 2007), which reduce the thermal load inside the greenhouse, with minimum possible effect on PAR radiation transmission, have become a very promising cooling complement for greenhouses of tropical and subtropical areas.

An important number of such photo-selective materials and coatings which differ in their optical properties are being developed at the moment (Hemming et al., 2006), but the best possible material has not yet been found. The field testing of such coverings is a high investment research work, which consumes a great amount of both labour and time. For the greenhouse covering developers, it would be of great interest to have a simulation tool that could be used in early stages of development of the materials to know in advance the effect on the greenhouse climate of every material on a certain location, at a lower cost in time and money than experimental field tests.

Numerical CFD simulations have already been used to simulate the coupling of convective and radiation fluxes on a greenhouse both at night (Montero et al., 2004) and during the daytime (Bournet et al., 2006; Ould Khaoua et al., 2006). However, on these works, materials with different optical properties have not yet been simulated. The present work aims at studying the validity of 3D CFD to simulate the daytime temperatures, first inside a very small closed double compartment and then on two semi commercial size multi-tunnel greenhouses, covered with a standard three layers polyethylene film and a NIR-reflecting photo-selective film, respectively.

MATERIALS AND METHODS

Scale model measurements and transient simulation

On a first approach, experimental measurements of ambient and black body temperatures were performed for both materials (standard and photo-selective) on a small double closed compartment (no ventilation) in which the film sheets (152 x 152 cm) were placed simultaneously on the front and top of each compartment (Figure 1(a)), being both compartments and the rest of the faces isolated from the outside with polystyrene panels (thickness 10 cm) painted in black on their inner face to avoid undesired reflections. The double compartment's top faces, covered with both materials, had a certain slope to the south (Figure 1(a)). Inside both compartments, 20 cm below the upper plastic film sheets, and approximately 30 cm in front of the back panels, three different sensors were attached to a metallic support: a net radiation sensor (Thies, model 7.1415.20.000), a ventilated pt-100 to measure ambient temperature and a thermocouple attached to a small black plastic object to measure black body temperature. All the data were stored in two data-loggers (Delta-T, DL2e; Thies Clima, DL15) located behind the compartments to avoid interference.

Measurements were performed at two different times (early morning and midday "solar time") on the the 6th and 7th of June (2006): completely clear days with wind velocities below 1 m/s, to avoid convection phenomena with the exterior, on periods of less than 15 minutes, to avoid excess heating of the closed compartments affecting the sensors.

After the experimental measurements, a CFD 3D model of the compartment was modelled and meshed (Figure 1(b)) including two boundary layers on the compartment faces covered with both plastic films. The total number of volumes was slightly above 300.000. The problem was set up as a transient heating simulation on a closed domain. To simulate solar radiation, the solar load model included in the solver is used (solar ray tracing method), which sets the sun direction vector and the intensity of solar radiation (direct and diffuse) reaching the model from corresponding data of orientation of the computational domain, latitude, longitude, time zone, date, solar time and a cloudiness factor (0-complete covering to 1-clear sky). Data corresponding to our case are gathered on Table 1. The solver is set to distribute the heat from the walls directly to the adjacent fluid cells. Internal re-radiation inside the compartments is simulated with the P1 radiation model. The heat convection to the outside of the computational domain is taken into account only at the plastic film walls, due to the isolation of the rest of walls, using a transient outside temperature profile during the measurement period and a heat transfer convection coefficient. After activation of the energy equation and gravity, the materials (air, expanded polystyrene, standard plastic film and photoselective film) physical properties are set, choosing the Boussinesq approach to cope natural convection processes. Outside initial ambient temperature (304 K) and initial black body temperatures are set, corresponding to the midday measurement of the 6th of June (328.4 K for the standard film and 322.6 K for the photoselective film). The k-ε RNG turbulence model was selected, activating the thermal effects-full natural convection options. The heat and radiation boundary conditions (including optical properties of both films provided by Repsol Y.P.F.) for all the boundaries of the model are gathered in Table 2. For pressure discretization, the Body Force Weighted model is used and for the coupling between pressure and velocity, the PISO algorithm is chosen, deselecting all the equations and performing a first calculation auto-saving the transient solar load data every 60 seconds, with a maximum number of iterations per second set to 1. The transient calculation is then performed with the parallel solver activating all the equations (energy, momentum, etc.) updating solar data every minute and setting 10 iterations per second, for a total calculation time of 900 seconds.

Full size greenhouse measurements and steady state CFD simulation

Two analogue multi-tunnel asymmetric greenhouses located in Almería (Spain) were covered respectively with the standard polyethylene film and the photo-selective (NIR-reflecting) film (Figure 2). Each greenhouse had 8 spans (with ridge oriented east-west surface of 2,500 m^2 (semi-commercial size). Each greenhouse had one roof flap vent oriented south per span and two rolling vents on the north and south sidewalls. All the greenhouse vents were covered with a 32% porosity anti-insect screen. The side parts of each span (east and west) were covered with polycarbonate, to provide more resistance to the wind. Each greenhouse had two aspirated psicrometers (dry and wet bulb pt-100, Priva) located in the middle of the third and sixth span, 2 m over the greenhouse floor. At the moment of the measurement (09/10/2006), the greenhouse had a very small tomato crop (transplanted on 09/06/2006).

The experimental greenhouse was modelled in the pre-processor, on a first step, including an outside computational domain, and simulations were performed including only the mass transfer, for the 09/10/2006 at 12:00 solar time, with all the greenhouse vents fully opened. Outside climate parameters were: temperature 303.75 K; wind velocity 3.3 m s^{-1}; wind direction 120.3º; global radiation 540.8 w m^{-2}. The standard k-ε turbulence model was used and the wind driven natural ventilation simulation converged. Once convergence was reached, air velocity profiles on the greenhouse vents were saved. On a second step, the outside computational domain was eliminated, energy equation, gravity and the solar load model activated, imposing the measured radiation (direct and diffuse) values as input values for the solar ray tracing method, together with the sun direction vector. Material physical properties were introduced (standard and photoselective plastic film, polycarbonate and sand mulch covering the greenhouse floor), activating the Boussinesq method for density calculations. In relation to the boundary conditions, the previously saved air velocity profiles were activated for each greenhouse vent. In the present case, outside wind velocity was above 2 m s^{-1}, and according to Boulard et al. (1996), buoyancy effect can be neglected, so we can assume the air velocity profiles will not be affected by buoyancy. The optical properties of the different materials can be found on Table 2.

RESULTS AND DISCUSSION

Scale model measurements and transient simulation

Figures 3(a), (b) and (c) and 4(a), (b) and (c) show the evolution of the black body and ambient temperatures at different times for the two studied materials (standard and NIR-reflecting photoselective). For black body temperature, it can be observed, that the NIR-reflecting material has a cooling effect in relation to the standard film, with temperature differences which become larger from the morning (≈ 5 ºC) to midday (≈ 8 ºC), as radiation levels increase. However, for ambient temperature, the temperature differences are almost inexistent in the early morning, and appear with higher radiation levels, never being as large as the black body temperature differences. When considering the CFD simulations, Figure 4 shows the evolution of the experimental and CFD simulated black body temperatures for both materials. Experimental values are an average of approximately 6ºC higher than the simulated values for the whole measurement. These differences can be explained because in the experimental measurement the black body temperature corresponded to a small object whereas the CFD simulated value has been considered as the average temperature of the back wall. The use of a more accurate radiation model (surface to surface) could improve the result. However, if we represent the evolution of the black body temperature difference between both materials (two different compartments) (Figure 5), we can observe the CFD prediction is very accurate in relation to the experimental measurement. Figure 6 shows vertical temperature contours at the end of the measurement period, at two different distances from the back walls of the two compartments. It can be seen, as both compartments present similar temperature patterns, showing the left compartment, with the standard plastic film, higher temperatures than the right compartment, covered with the “cooling” material.

Full size greenhouse measurements and steady state CFD simulation

Table 4 shows the measured and the CFD simulated values of temperature in both greenhouses, with the two tested materials (standard and NIR-reflecting photoselective). All values correspond to midday (solar time), and the first thing to highlight is that temperatures were slightly lower in the greenhouse covered with the photo-selective film, specially when comparing the sensor located below the sixth span starting from the south, which is, in both cases measuring lower temperatures than the north sensor. These differences prove that the temperature field in large greenhouses are far from being homogeneous, and are strongly dependent on the natural ventilation processes. The CFD simulated absolute values corresponding to the exact coordinates where aspirated psicrometres were located, also show lower values under the photoselective film. These punctual values do not differ much from the measured values (around 2 ºC), except for the sensor located in the north of the photo-selective greenhouse. When comparing average differences (Table 4), a very good agreement can be observed between measured and simulated values, for both punctual values and values averaged for the whole domain. This good agreement proves that CFD simulations can be a very promising tool to simulate the temperatures under covering materials with different optical properties.

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Tables

Table 1. Solar calculator parameters of the solar load model for the transient simulation.

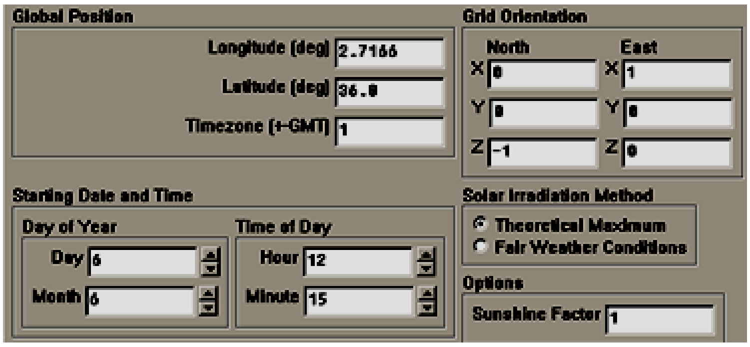
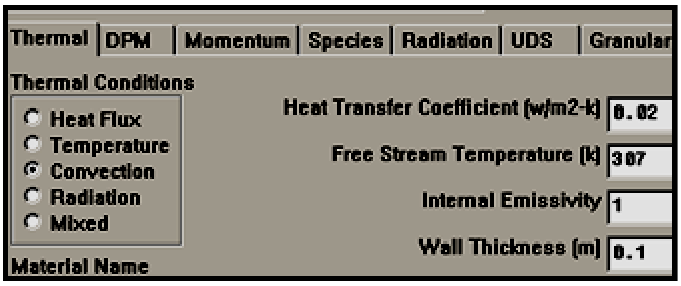
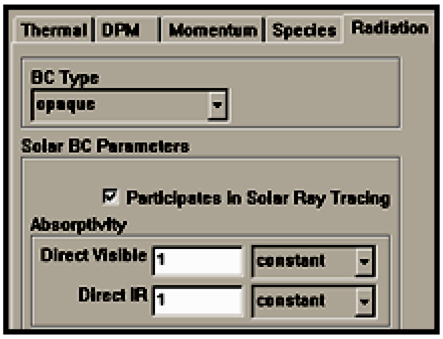
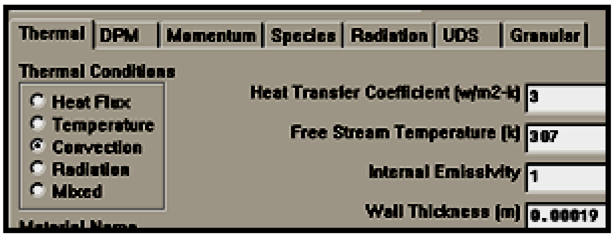


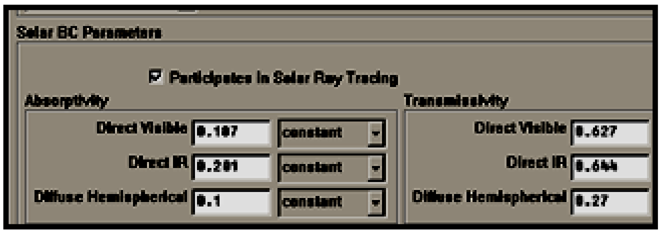
Table 2. Thermal and radiation boundary conditions for the different materials.



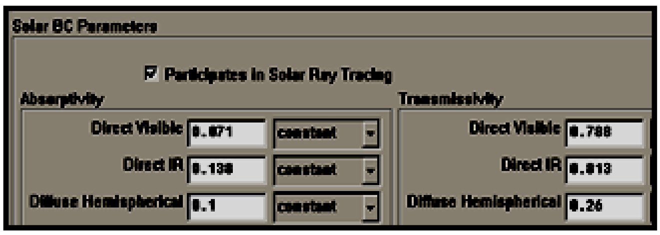


Insulated walls (polystyrene)





Photoselective film



Standard film

Table 3. Experimental and CFD simulated temperature values.

	Measured (ºC)		CFD (sensor exact position) (ºC)		CFD (whole volume average value) (ºC)	
	South	North	South	North		
Standard film	42.1	40.6	41.16	43.83	42.8	39.13
Photoselective film	40,2	35	38.11	40.78		
	ΔT_{south}	ΔT_{north}	ΔT_{south}	ΔT_{north}		
Temperature difference between both materials (ºC)	1.9	5.6	3.05	3.05	3.67	
Average difference (ºC)	3.75		3.05			

Figures

Figure 1(a). Experimental box covered with the two studied materials (A-photoselective and B-standard)

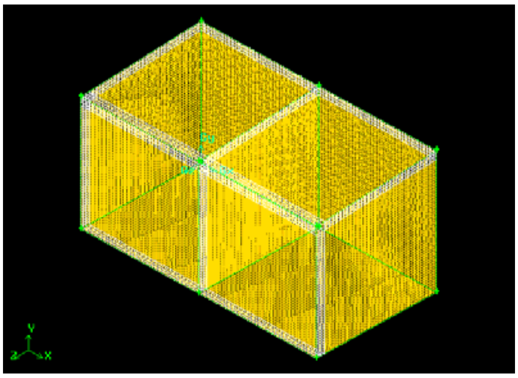


Figure 1(b). CFD model of the double compartment box already meshed.

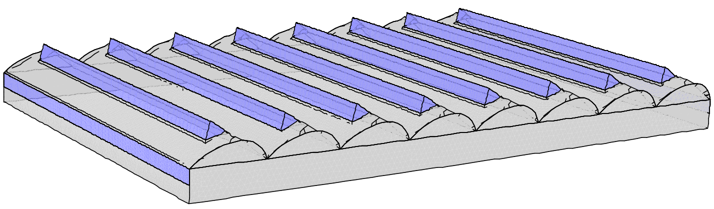


Figure 2. CFD model of the experimental multi-span greenhouse.

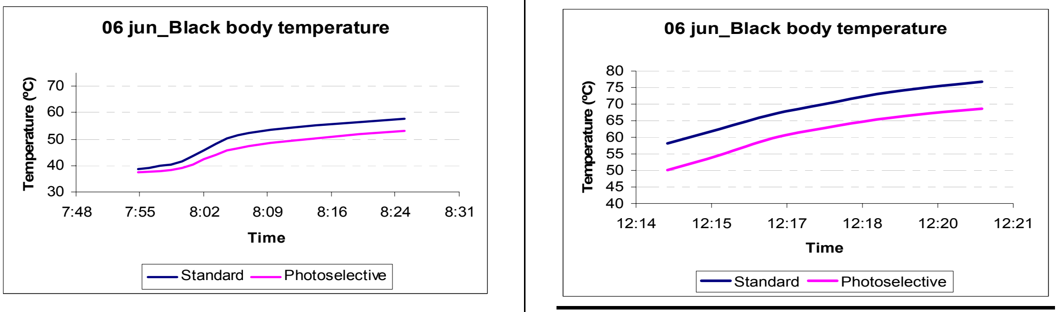


Figure 3(a), (b) and (c). Evolution of the black body temperatures under both materials (standard and photoselective) at different times

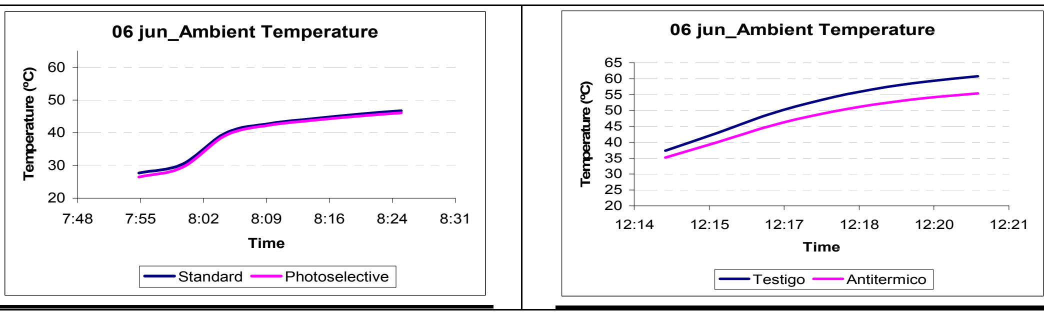


Figure 4(a), (b) and (c). Evolution of the ambient temperature under both materials (standard and photoselective) at different times

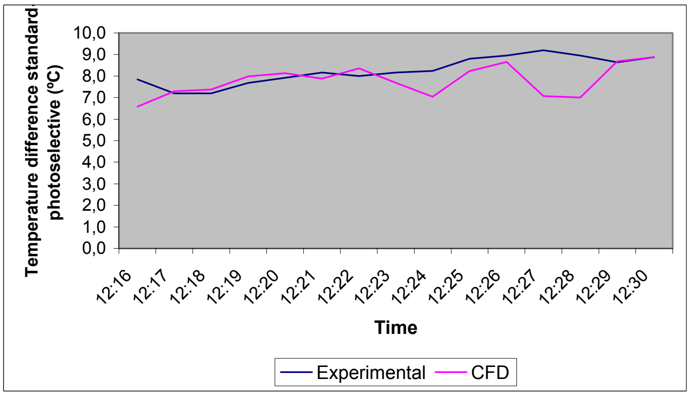


Figure 5. Evolution of the experimental and CFD simulated temperature difference (ºC) between both compartments.

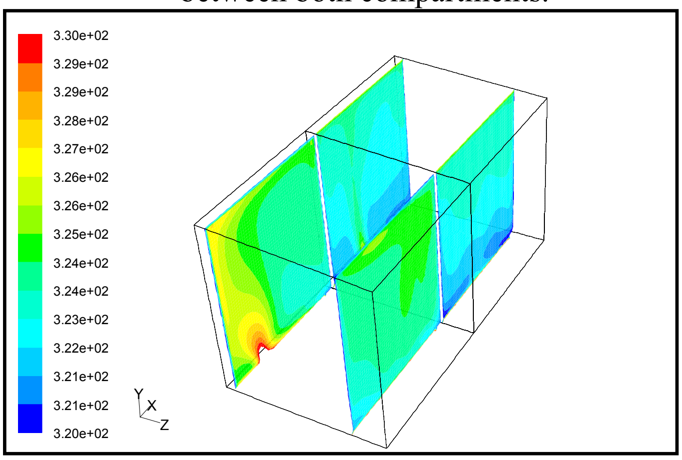


Figure 6. Absolute temperature vertical contours in both compartments.