CFD Simulations of the Distributed Climate Time-Evolution inside a Glasshouse at Night

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Abstract

Following the rise of energy costs and fuel scarcity, energy becomes today one of the main greenhouse crop production expenses. In this context, growers have to adapt their production system and climate management strategy in order to remain competitive, particularly at night when heat supply is often required and risk of condensation is enhanced. Numerical tools such as Computational Fluid Dynamics (CFD) can help predict the climate inside a greenhouse. CFD however is still scarcely applied in a dynamic way (Nebbali et al., 2011) and under night conditions (Montero et al., 2005). The aim of this study is to implement an unsteady 2D CFD model to predict the time-evolution of greenhouse temperature and humidity distributions all night long in winter, taking account of both radiative transfers and crop interactions with the inside climate. Beyond the classical conservation equations, a radiative submodel and a crop-submodel were activated. The latter takes account of both the heat and transpiration fluxes induced by the plants and their associated mechanical resistances which depend on the transfer mechanisms from the plant to the air. The boundary conditions were modified at each time step. Simulations were performed for a clear night on the basis of data collected in winter 2011 inside a 100 m^2 Venlo glasshouse with Impatiens New Guinea crop grown on shelves. Numerical results were validated against data recorded inside the greenhouse: roof temperature, inside air temperature, transpiration flux and air humidity. They highlight the influence of the dynamic boundary conditions on the evolution of the microclimate inside the greenhouse. This study demonstrates the ability of the CFD code to simulate the greenhouse climate evolution with realism. It also suggests a potential exploitation for designing the heating devices in order to optimize the inside climate and energy consumption for various outside conditions.

INTODUCTION

During winter at night, it is common to keep the greenhouse vents closed as long as possible in order to limit heat losses and avoid excessive heating. But following the decrease of the inside air temperature combined with plant transpiration, the relative humidity may strongly increase, which may enhance risks of condensation and development of fungal diseases. The most widespread method to cope with this problem is to evacuate excess humidity by opening the vents. However, with this method, while humidity is evacuated through the vents, cool air enters the greenhouse so that heating is required to restore a temperature adapted to the crop needs. Such a procedure is however not satisfactory due to the fact it causes an important energy waste.

In the context of natural resource scarcity, optimizing energy consumption becomes one of the main concerns of growers who take care to minimize their production cost to

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remain competitive. They pay a particular attention to better control their greenhouse system management in order to reduce greenhouse inputs (energy, water, CO_2…). This implies a better knowledge of the physical mechanisms driving the climate inside greenhouses.

To reach this goal, Computational Fluid Dynamics is an efficient tool which makes it possible to access the entire distribution of the climatic parameters inside the greenhouse. The device also enables to test different contrasted situations without expensive costs. Up to now however, only few CFD studies were devoted to night time conditions in greenhouses when the heating and dehumidification needs are nevertheless the highest. Montero et al. (2005) studied the night-time greenhouse climate using a 2D steady state model including a radiative submodel which takes account of the radiative flux exchanged between the greenhouse and the sky. No heating system was used in their study and the impact of the crop on the greenhouse climate (and therefore the humidity rate) was not considered. Piscia et al. (2012) validated a transient 3D model which simulates condensation phenomena that may occur on walls. Yet, in this study, the crop was only considered as a source of water vapor. No interaction with the climate was considered so that the crop behavior was independent of the climatic conditions, which remains questionable.

The objective of the present study is to validate an unsteady 2D model including mass and radiative transfers, as well as the interaction between crop and inside greenhouse climate in order to predict the time-evolution of both temperature and humidity distributions all night long.

MATERIALS AND METHOD

Site, greenhouse description, and measurements

In order to provide input and validation data, experiments were conducted inside a 100 m² compartment of a Venlo type greenhouse located in Angers (47° 28’ North, 0° 33’ Est). Potted Impatiens (Novae-Guinea, cv. ‘Sonic Scarlet’) were uniformly placed at 80 cm height on four shelves covering 18 m² of the greenhouse ground surface. The average plant height was 30 cm, the density of the canopy was 10.6 plants per m² and the leaf area index (LAI) was 4.2. During the field survey, the canopy covered 100% of the shelves, no shading screen was used and the roof vents were closed. Flowers were regularly removed and plants were watered once a day by flooding the shelves with a complete nutrient solution.

A set of sensors was used to measure the climate characteristics inside the greenhouse (Fig. 1). The temperature (T_a) and relative humidity (RH) of the air were measured by aspirated sensors (Vaisala HMP45C, Campbell Scientific Ltd., Antony, France) located 15 cm above the crop, inside the crop and under the shelves. A sonic anemometer (CSAT3, Campbell Scientific Ltd., Antony, France) monitored the air speed (V) 15 cm above the crop. The temperature of the leaves of the upper (T_{l1}), middle (T_{l2}) and bottom (T_{l3}) part of the crop were recorded with copper-constantan (Cu-Cs) thermocouples glued to the underside of plant leaves and then averaged. A balance was used to estimate the crop evapotranspiration and two fluxmeters (Captec, France) measured the greenhouse ground surface heat fluxes. Outside the greenhouse, an aspirated Vaisala HMP45C sensor measured the air temperature (T_{out}) while the downward and upward long wave radiations were recorded by a CNR1 pyrradiometer (Kipp & Zonen, The Nederlands). All the above-mentioned parameters were measured every 3 s and averaged online over 10-min periods with a data logger system (CR3000 and CR7, Campbell Scientific Ltd., Antony, France). The experiments were carried out from February to March 2011. For the purpose of the study, a clear night (March 3rd) was analysed.

Numerical Method

The CFD simulations were carried out with the commercially available CFD package, AnsysFluent 13. This numerical tool solves the 2D convection diffusion equations with the finite volume technique. Assuming that the fluid is uncompressible, the transport equations may be written in the general form:

$$\frac{\partial \phi}{\partial t} + \frac{\partial U\phi}{\partial x} + \frac{\partial V\phi}{\partial y} = \Gamma \Delta \phi + S_\phi \tag{1}$$

where Φ represents the concentration of the non-dimensional transported quantity, namely momentum, mass (air and water vapour) and energy, U and V are the components of the velocity vector, Γ is the diffusion coefficient, and S_Φ is the source term. The density depends not only on the temperature, but also on the water vapour content in the air and the buoyancy force is added as a source term in the momentum equations. The standard k-ε turbulence model (Launder and Spalding, 1974) was adopted. Radiative transfers were simulated through the resolution of the radiative transfer equation using the Discrete Ordinate (DO) method (Bournet et al., 2007). From the mechanical point of view, the crop may be considered as a porous medium obstructing the inside airflow and inducing a pressure loss estimated from the Darcy-Forchheimer's law. The crop activity is modelled by a user defined function which calculates the energy balance over the leaves $Rn=E+H$ (where Rn is the absorbed net radiation flux, and H is the sensible heat flux) in order to estimate the latent heat flux (E) due to plant transpiration, which is a source term of the water vapour conservation equation.

The calculation domain was divided into 36960 cells restricted to the experimental greenhouse compartment and the outside air just above. In order to reduce the interference of the outlet condition on the calculated flow, the adjacent downward compartment was also included in the calculation domain. The initial conditions were obtained by calculating under steady state conditions the distribution of the climatic parameters performed by the CFD tools using the boundary conditions at 11 pm. The initial humidity rate was deduced from measurements at the same time. The boundary conditions (Fig. 2) were directly inferred from the measurements and modified at each time step (Fig. 3). Along the lateral walls of the greenhouse, fixed temperatures were set while a heat flux was imposed along the ground surface in order to take account of the heating. The heat flux intensity corresponded to the average values of the two ground fluxmeters. An inlet airflow with a fixed temperature was considered at the upwind vertical boundary of the calculation domain whereas an outflow condition with zero gradients except for the pressure was chosen at the exit. Lastly, a radiation sky temperature (T_{sky}) was introduced at the upper limit of the calculation domain and along the inlet and outlet boundaries. Its value was deduced from the long wave radiation measurements according to the following expression:

$$W_{sky-radiation} = \sigma T_{sky}^4 \tag{2}$$

where σ is the Stefan Blotzmann constant (σ=5.67.10^{-8} W m^{-2} K^{-4}). Calculations were carried out under unsteady conditions considering a 10 minute time step from 11 pm to 6 am.

RESULTS AND DISCUSSION

As shown in Fig. 3, even if the outside air temperature (T_{out}) decreases along the night, from 277 K to 274 K, the inside air temperature remains quite constant (around 289 K) due to the increase of the heating system intensity (Fig. 4). The simulated inside air temperatures above the crop (T_3) and under the shelves (T_1) are slightly underestimated whereas the within-canopy air temperature (T_2) is slightly overestimated. Nevertheless, the simulated time evolutions of the air temperature inside the greenhouse follow the experimental curves with differences lower than 1 K (Fig. 4), which evidences the ability of the model to correctly predict the thermal behaviour of the greenhouse.

The comparison between simulated and measured air temperatures shows that the predicted temperature heterogeneities are lower than expected (Fig. 4). This may be due to the fact that the simulated air speed reaches 0.5-0.6 m s^{-1} inside the greenhouse (Fig. 5) which seems to be largely overestimated for a closed greenhouse compared with air speed measurements (0.15 m s^{-1}). Such high air speeds induce a high level of mixing and smooth temperature gradients as shown in Fig. 6. The overestimation of the roof temperature by CFD may also be due to these relatively high air speeds which enhance convective exchanges (Fig. 4).

The time evolutions of the simulated and measured averaged leaf temperatures were also compared as well as the within-canopy air temperatures (Fig. 7). At the beginning of the night, the experimental and numerical air-to-leaf temperature differences are both positive. However, during the night, the experimental value of the air-to-leaf temperature difference remains positive and roughly constant whereas the simulated one decreases and becomes negative. At the end of the night, the simulated leaf temperature is greater than the air temperature. The predicted leaf temperature evolution is therefore qualitatively wrong even if it seems to exert a slight influence on the simulated inside crop air temperature. The analysis of the simulated transpiration time-evolution may explain this behaviour: during the night, as no air leakages or condensation process are introduced in the numerical model, the simulated humidity rate increases in the greenhouse as shown in Fig. 8 (contrary to experimental observations where humidity remains almost constant). The air vapour pressure deficit then progressively reduces during the night as well as the simulated transpiration rate. Consequently, as no more latent heat is exchanged at plant level, leaf temperatures become higher than they should be. In Fig. 8, the humidity distributions show that the relative humidity is lower than 85% at 1 am but reaches 100% near the roof at 2 am, meaning that condensation may appears after 2 hours of simulation, in agreement with Piscia et al. (2012) results.

CONCLUSION

An unsteady CFD model including convective and radiative transfers as well as the interaction between the crop and the local microclimate was developed to study the night evolution of the greenhouse climate. The present study highlights the ability of the numerical tool to simulate the temperature inside the greenhouse even if the model appears to overestimate mixing inside the shelter. Overestimations of the inside air speeds also enhance heat exchanges along the roofs, which results in overestimated roof temperatures. The main weakness of the model lies in its disability to correctly simulate processes driving the humidity. The predicted humidity rate quickly rises probably because condensation and leakages for instance are not included although they strongly regulate the water vapour content of the greenhouse. The integration of these mechanisms would probably improve the performance of the model and the prediction of the humidity rate evolution inside the greenhouse in particular.

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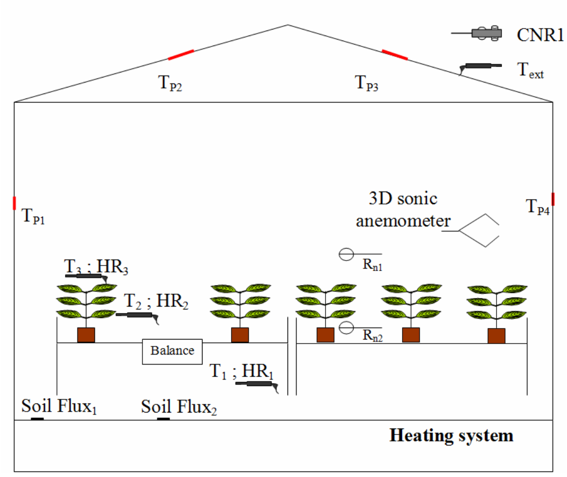


Fig. 1. Experimental setup.

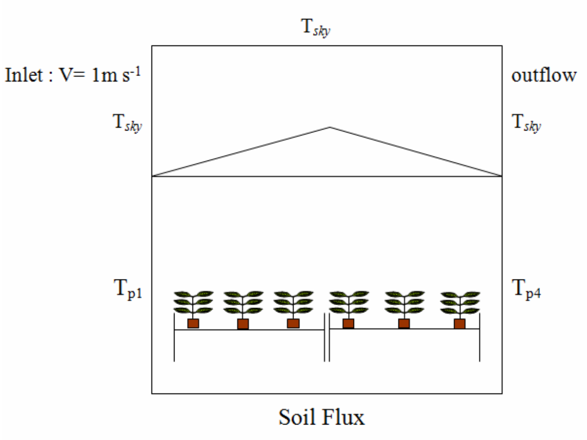


Fig. 2. Boundary conditions.

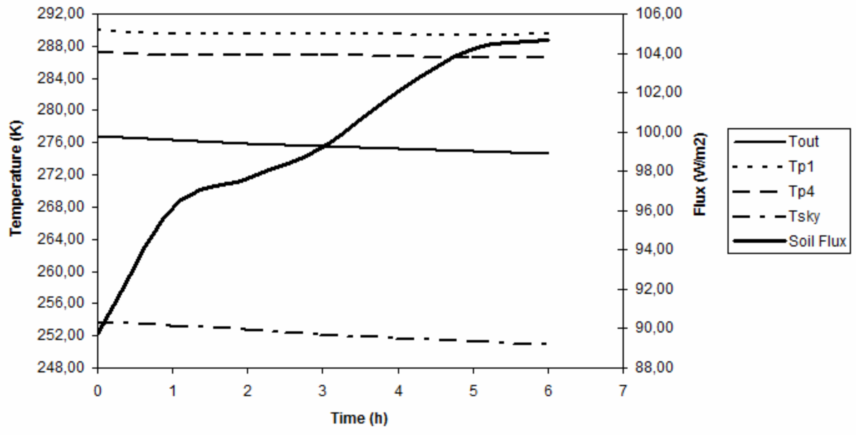


Fig. 3. Time evolution of the boundary conditions.

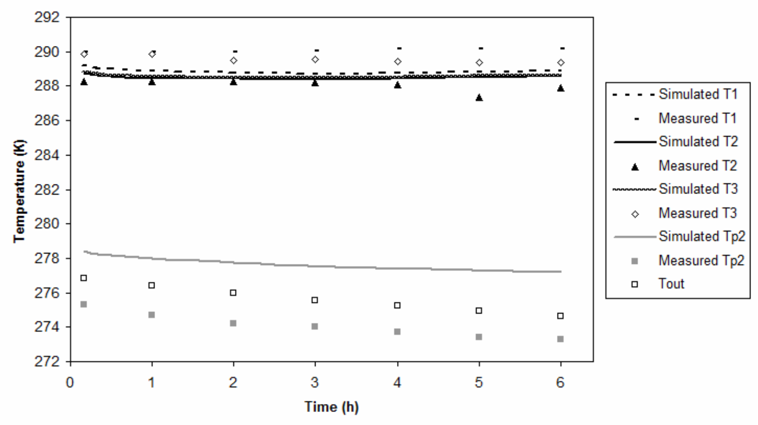


Fig 4. Time evolution of measured (dots) and simulated (lines) inside air temperature.

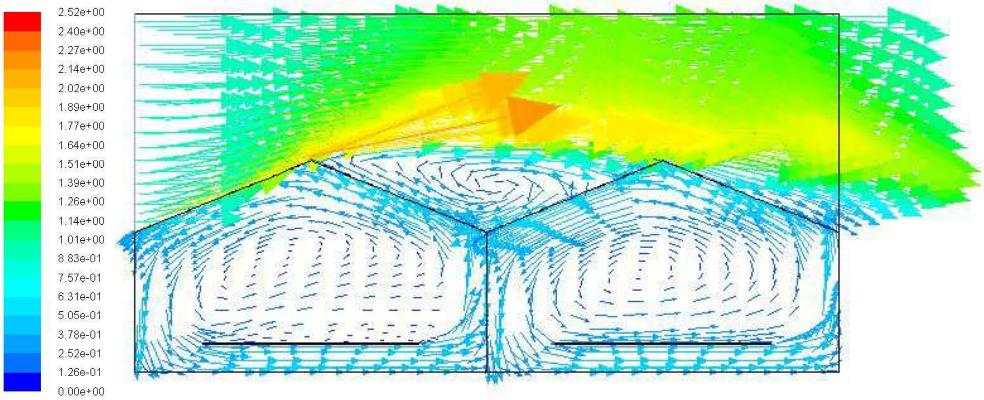


Fig. 5. Air speed distribution at midnight.

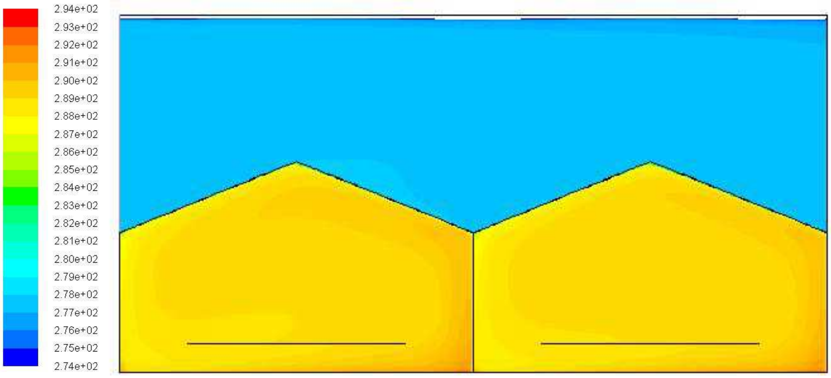


Fig. 6. Temperature distribution at midnight.

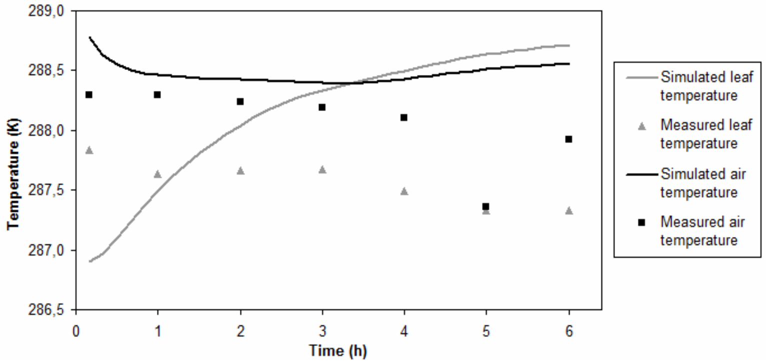
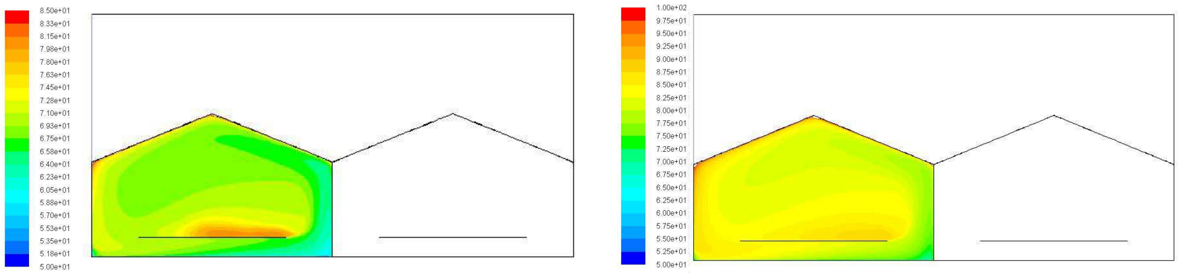


Fig. 7. Time evolution of inside crop air and average leaf temperature.



1 am

2 am

Fig. 8. Relative humidity distribution at 1 am and 2 am.