CFD determination of the climate distribution in a semi closed greenhouse with air cooling

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Abstract

This paper presents the results of the simulation of the temperature and air humidity distributions in a 960 m² semi closed greenhouse with a tomato crop and equipped with fourteen air cooling and dehumidifying ducts. These units are distributed between the crop rows and the sucking inlets are alternately located at high or low locations. The computational model of the aerial domain was developed using the Fluent Computational Fluid Dynamics code. For simulating radiative exchanges, a Discrete Ordinates (DO) model was considered. Sensible, latent and radiative heat transfers together with crop activity (stomatal resistance) and induced water vapour transfers were computed within the crop stands using a porous and semi-transparent medium model. In order to limit both computing time and mesh size, the geometric domain was limited to the greenhouse walls. Experimental conditions for temperature and humidity conditions were applied to the outlets of the ducts. Air leakages and airflow through the vents during the opening period were simulated with sink terms located on the mesh connected with the roof and the walls. Simulations were performed for a single summer day from 8:00 am to 22:00 pm with a 30 minutes time step. A new set of boundary values was applied before each simulation. Simulated and measured values of temperature and water vapour concentration inside the greenhouse are presented and commented together with a sensibility study on the influence of the air conditioning device.

Keywords : simulation, air conditioning, crop model, climate distribution, fluid dynamics

INTRODUCTION

The concept of closed or semi-closed greenhouses theoretically allows a large reduction of energy costs, a better protection against pest invasions and CO_2 enrichment at high concentration during vent closing periods in semi-closed greenhouses. Since the last decade several studies devoted to this concept have been published (Bakker *et al.*, 2006; De Zwart and Kampkes, 2007). Experimental facilities have been developed in the CTIFL Experimental Center of Balandran in South France, consisting of a semi-closed greenhouse connected to an aquifer thermal energy storage system that allows the use of stored thermal energy in the winter period (Grisey *et al.*, 2011). Concerning the inside climate distribution, both experiments and CFD simulations have been performed and the first results regarding the distribution of temperature and humidity have been presented in a former paper (Pouillard *et al.*, 2011). Measurements and simulations of the evolution of the CO_2 concentration have also been performed for a summer day with the use on a photosynthesis model of the crop (Roy *et al.*, 2013). Temperature and humidity distributions have also been investigated for this summer day and are presented and compared for both closed and opened vents periods. The simulations take into account measured values for the

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determination of the blowing conditions in the air conditioning device. Additional simulations present the influence of the air conditioning device setting (set-point for water vapour concentration) on the humidity pattern inside the crop and inside the whole greenhouse.

MATERIALS AND METHODS

The greenhouse

The description of the semi-closed greenhouse system and the distribution of the experimental sensors has been presented in previous papers (Grisey *et al.*, 2011; Roy *et al.*, 2013) and will not be repeated in details here. The air conditioning device is made up of a reversible heat pump that allows the transfer of heat between the water storage tanks and the conditioned air. Air is sucked up through 14 inlets ducts alternately located on the upper and lower part of the greenhouse in order to avoid a large thermal stratification of air inside the greenhouse. Conditioned air is blown just under the crop rows through 14 soft plastic perforated sleeves. Humidity and temperature sensors have been located in both the inlet ducts and the outlet sleeves and the measured values are used in the CFD code as boundary conditions for the simulation of the air conditioning device.

The model

The 3D calculation domain is limited to the greenhouse. The surrounding environment was not taken into account in order to avoid too large mesh size and computational time. Fig.1 shows the sketch of the domain that consists in the greenhouse (length = 40.4 m; width = 24 m; height = 6.4 m); the crop: 16 tomato rows (length = 33 m; width = 1 m; height = 3 m) and the air conditioned ducts made up of 14 alternate upper and lower inlet ducts connected to 14 perforated outlet sleeves located under the crop rows. The total meshing of the domain (greenhouse and air conditioning system) represents one million cells.

The 3D conservation equations for mass, momentum and energy are solved together and coupled with the radiative transfer equation (RTE) in transparent (air) or semi transparent (crop rows) media using the discrete ordinates (DO) model which performs a space discretisation in several solid angles and consider several wavelength bands (Nebbali *et al.*, 2012). The coupling between radiative and convective transfer was computed for the solid and fluid interfaces and the crop cover was considered as a semi transparent medium. The net short waves (SW) radiative balance for each mesh of the crop cover was provided by the DO model and added to the net long wave radiative balance. This global net radiative flux was considered as the source term of the energy balance equation that performs the computation of sensible and latent heat exchanges between each cell of the crop cover and air. This energy balance was solved by means of a specially developed user defined function (UDF) (Boulard and Wang, 2002). The governing laws for crop cover exchanges together with the boundary conditions have been described in a previous paper (Pouillard e*t al.,* 2011) for momentum, heat and water vapour. The resolution of these conservation equations was performed with the CFD code Fluent v.15.0 that permits the determination of pressure, velocity, temperature and water vapour concentration for every mesh node.

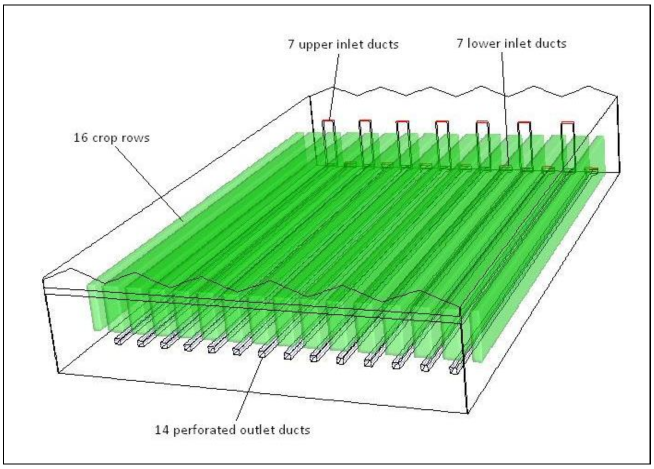

Figure1. Layout of the greenhouse and the air conditioning device

RESULTS AND DISCUSSION

Likewise for the CO_2 concentration evolution that was described in a previous paper (Roy *et al.*, 2013) we present a set of steady-state simulations with 30 minutes intervals for the day of June 30th 2011 between 8:00 am and 10:00 pm. The greenhouse was kept closed during the main part of the day except between 12:00 am and 4:30 pm when the outside temperature became too high to maintain reasonable conditions inside the greenhouse despite the working of the air conditioning device. Boundary conditions for temperature and SW radiation were deduced from temperature measurements on the sidewalls, on the ground and on the roof of the greenhouse and from global and net radiation measurements over the crop rows. The modeling of the airflow corresponding to leakages and vent opening periods constitutes a problem because of the limitation of the domain to the inside of the greenhouse. This problem was solved considering a uniform source/sink term for energy and species equations in the cells corresponding to the boundary regions in contact with the sidewalls and the roof. Air leakages were determined with a gas tracer technique and the airflow G through the opening vents was estimated with the wind and chimney effect relation (Boulard and Baille, 1995; Roy *et al.*, 2002):

$$G = (\frac{S_o + S_l}{2}) C_d [2g(\frac{\Delta T}{T})(\frac{H}{4}) + C_w U^2]^{0.5} \quad (1)$$

Where S_0 is the opening vents area and S_l the leakages area in m^{-2}. The first term in the sum between brackets corresponds to the contribution of the chimney effect (T in K and ΔT are respectively the external air temperature and the difference of air temperature between inside and outside of the greenhouse; g is the gravitational acceleration in m s^{-2} and H is the vertical height of the openings in m). The second term represents the external wind effect (U in m s^{-1} is the wind speed). C_d and C_w are respectively the discharge coefficient of the openings and the wind effect coefficient. These coefficients were estimated for the greenhouse: C_d =0.7 and C_w=0.11. Time courses for measured temperature and water

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vapour rate are presented on Figures 2 and 3 for both lower and upper inlets and on can observe that temperature are almost equal while the water vapour ratio presents sensible difference: the water vapour concentration is 6 ·10^{-3} kg kg^{-1} for lower inlet ducts and reaches 1.2 10^{-2} kg kg^{-1} for upper inlet ducts. The reason for this variation stands both in the water vapour concentration difference between the upper and the lower inlet air and in the different performance of the air conditioning devices.

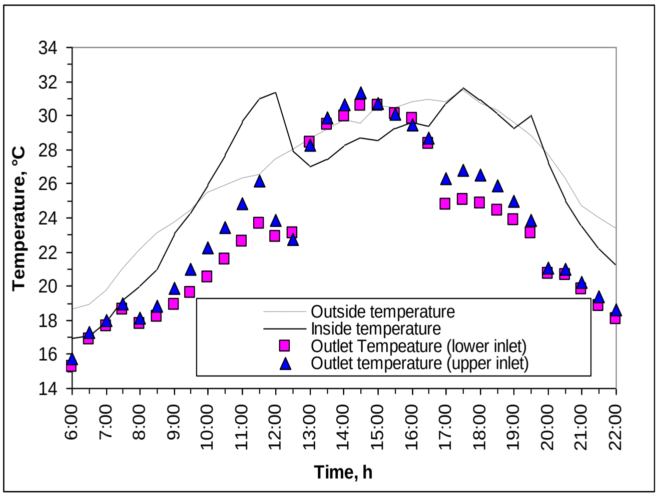

Figure 2. Time course for measured temperature in the air conditioning device outlet.

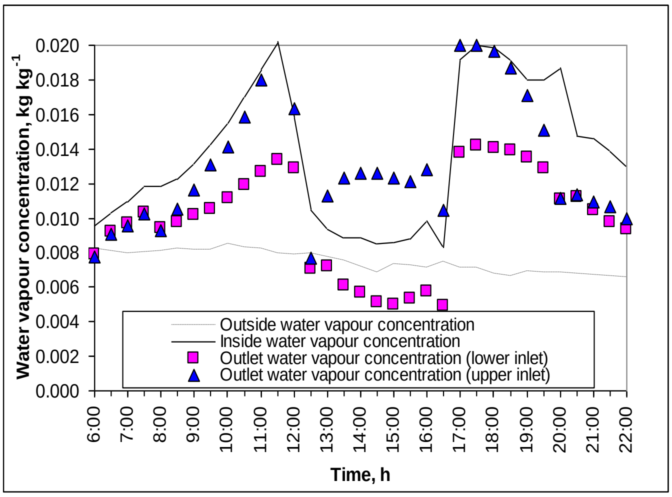

Figure 3. Time course for measured water vapour concentration in the air conditioning device outlet.

Time course for the simulated (8:00 am to 10:00 pm) and measured (8:00 am to 7:00 pm) mean temperature is presented on Figure 4. As previously noticed for CO_2 concentration (Roy *et al.,* 2013) simulations and measurements are in good agreement for closing vents periods (before 12:00 am and after 16:30 pm).

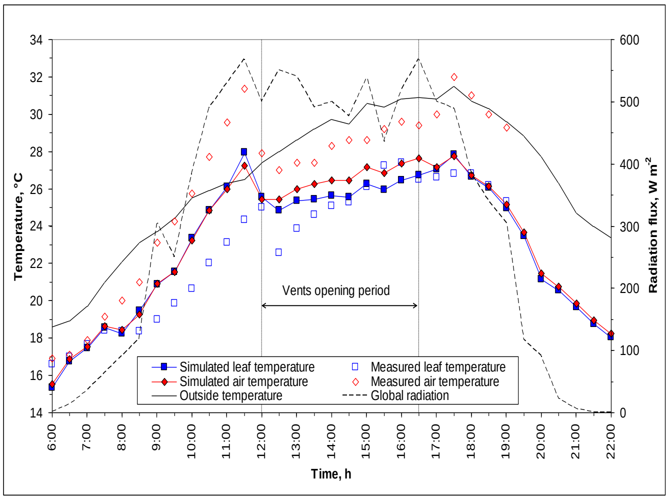

Figure 4. Time course for mean temperature in the crop.

A similar time course is presented on Figure 5 for the water vapour concentration.

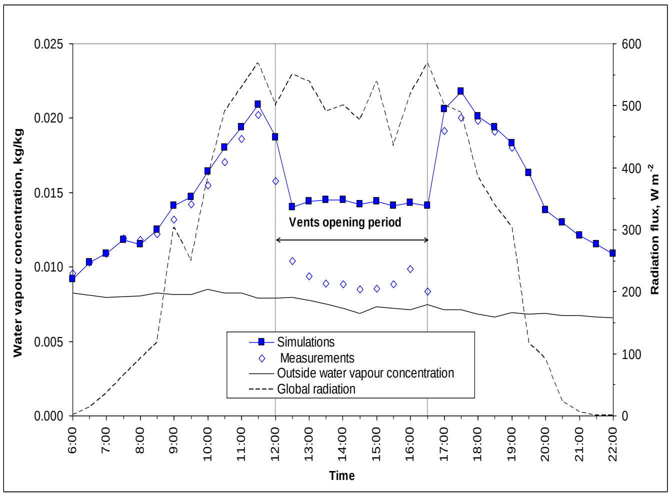

Figure 5. Time course for the mean water vapour concentration in the crop.

Measured and simulated values are very similar for the closed vents periods but the difference reaches 5 $\cdot 10^{-3}$ kg kg^{-1} during the opened vents period. This can be explained as the consequence of the assumption of a source/sink term on the sidewalls and the roof instead of a natural ventilation airflow through the opened vents and constitutes the limitation of the model based on a domain including only the greenhouse without its direct environment. The influence of the flow-rate produced by the air conditioning device on the inside temperature and water vapour concentration was also investigated. For that purpose, a set of flow-rates corresponding respectively to the experimental value *Q= 7.6 m* s^{-1}*, to 2Q* and to *3Q* have been used to simulate the climate parameters for different times. Results are presented on Figure 6. When *Q* increases, its influence on the climate parameters in the crop increases too. Temperature keeps constant values during the open vents period (14:00 and 16:00 on Figure 6) and the difference between the water vapour concentration values keeps constant for every time value (Figure 7). The evolution of the concentration is important when the airflow rate increases from *Q* to *2Q* and concentration remains almost constant when airflow rate is increased to *3Q*.

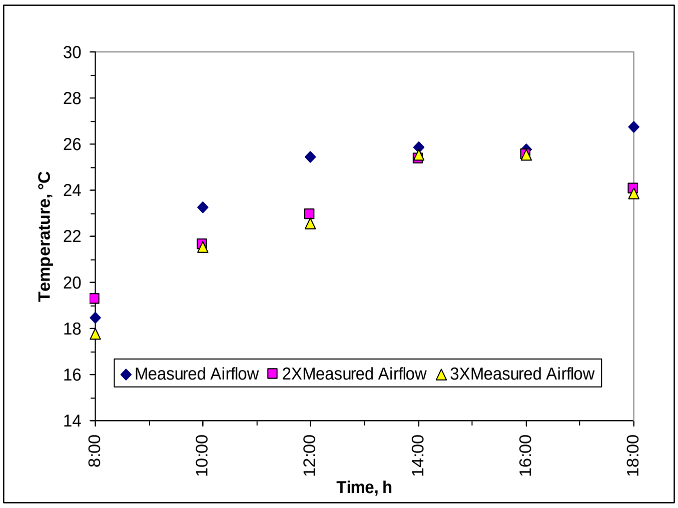

Figure 6. Time course for the simulated mean crop temperature for different airflow rates.

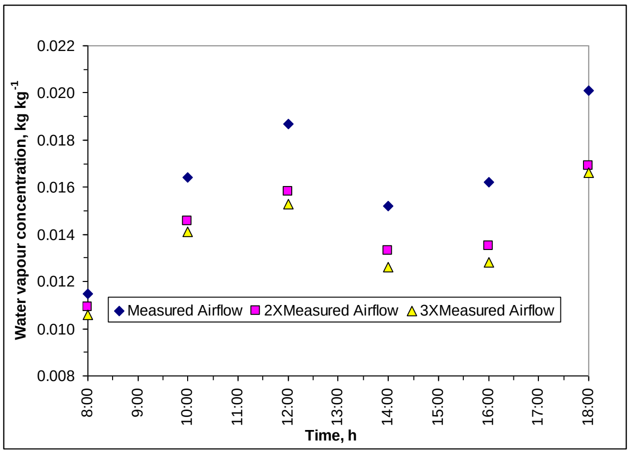

Figure 7. Time course for the simulated mean crop water vapour concentration for different airflow rates.

The simulated water vapour concentration patterns are presented on Figure 8 for the mean values in the crop at 4:00 pm (open vents): the distributions for *2Q* and *3Q* are very similar. One can conclude that an important increase of the airflow rate doesn't bring a significant modification of the inside climate. The evolution of the concentration pattern is presented on Figure 9 for 3 time values. One can observe its important increase in the crop from 10:00 am to 6:00 pm and the development of a low value region in contact with the sidewalls and the roof at 4:00 pm and more generally during the open vents periods (Figure 9b).

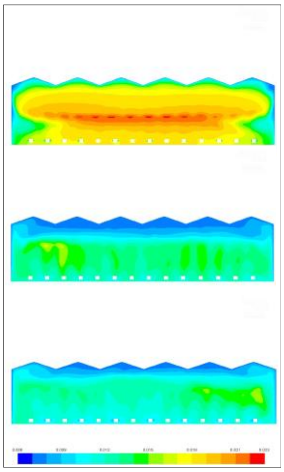

Figure 8. Simulated water vapour concentration in a median plane at 4:00 pm for airflow rates in the ducts equal to *Q*, *2Q* and *3Q*

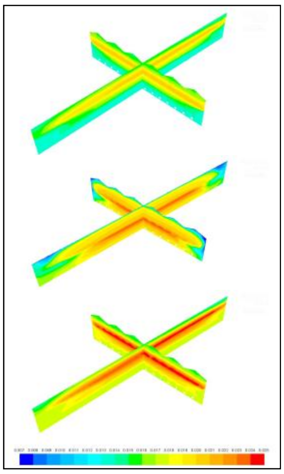

Figure 9. Simulated water vapour concentration in two cross-median plane at 10:00 am; 4:00 pm and 6:00 pm

CONCLUSION

The evolution of the climate conditions in a semi-closed greenhouse was simulated for a hot summer day with a specific model for heat and water vapour transfers between the crop and the inside air. The Discrete Ordinates radiation model was also used and the boundary conditions were experimentally determined with a 30 minutes period, as the domain is limited to the greenhouses sidewalls, roof and ground. The airflow through leakages and open vents was simulated as sink terms for energy and species transport equations in the cells adjacent to the sidewalls and the roof. Simulations and experimental values are generally in good agreement, however discrepancies appear for the water vapour concentration during the open vents period. These differences highlight the impossibility to obtain accurate simulation values with a limited domain when the roof vents are opened. For that configuration, virtual sink terms bring only an approximate performance of airflow through the vents. The influence of the airflow rate in the air conditioning device was also investigated. Simulations of temperature and water vapour concentration patterns inside the greenhouse show that a doubling of the experimental airflow rate leads to a sensible variation of the climate distribution inside the greenhouse. Higher values of the airflow rate don't bring further evolution of these parameters.

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