Development and Validation of a Global CFD Model of Heat, Water Vapour and Fungal Spores Transfers in a Greenhouse

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Abstract

This paper describes a global CFD model of heat, water vapour and *Botrytis c.* spores transfer in a three spans greenhouse. In addition to the integration of plant transpiration to the convective transfer which has been already presented in previous papers, we focus in this article on the description of a specific module to compute the effects of soil, insect-proof nets and vegetation rows on the deposition of Botrytis spores. It aims at the simulation of the spores concentration patterns in a greenhouse in relation with the external conditions and particularly the spore concentration.

The equations of flow are solved with the Fluent® CFD code and the standard k-ε turbulence model and we present specific models for the determination of source/sink terms in the equation of transport of a scalar that corresponds i) to the water vapour and ii) to the spore concentration in the airflow. Concerning the particles transport, three kinds of sink terms are considered for the soil, for the insect-proof nets and for the vegetation rows. The parameters of the model together with the experimental measurements and climate boundary conditions were determined in an experimental study for a rose greenhouse with roof and lateral vents equipped with insect-proof nets.

Comparisons with experimental results of greenhouse air exchange rates and inside climate (temperature and humidity) are presented and discussed together with measured and computed values of inside air spores concentration and deposit on the crop cover.

First results on distributed values of air flow, temperature, humidity and spores concentration and deposition fields within the greenhouse are presented and commented.

INTRODUCTION

Microclimatic parameters and particularly air temperature and humidity have long been recognised as key factors in the development of diseases caused by fungal pathogens and greenhouse climate management in relation to disease control (Nicot and Baille, 1996). We have therefore developed a global Computer Fluid Dynamics (CFD) model which allows simulating the major determinants of fungal development in greenhouses: the inside climate and chiefly air humidity, and the spores transfer and deposition on the crop cover.

Recent CFD developments for greenhouse climate modeling have shown that such approach constitutes nowadays a powerful tool for the determination of the climatic parameters prevailing in a greenhouse (Haxaire, 1999, Fatnassi et al., 2003, Molina et al., 2004). In order to have at one disposal a global model allowing for simulating both inside greenhouse climate and spore's transfer and deposition, we have started from previous models describing the greenhouse inside climate and its coupling with plant transpiration (Boulard and Wang, 2002) and we have added a new scalar: the spore’s concentration which is simulated using an Eulerian approach of particle transport.

This paper presents the first results of 2D numerical simulations of climate and spores transfer performed with the Fluent CFD code for a three spans greenhouse with roof vents and a side opening both equipped with insect-proof nets and its validation by means of experimental results obtained for the performing of a *Botrytis* spore balance of a rose greenhouse (Boulard *et al.*, 2007).

METHODS

The CFD code

The commercial Fluent (v. 6.1) code has been used to perform the simulations of the flow in the greenhouse. As low velocity fields are encountered for air flowing through the greenhouse, a precise modeling of free convection effects is required. Hence, a precise determination of temperature and humidity fields within the greenhouse and particularly in the crop stands is necessary to correctly compute the velocity fields. The energy and momentum equations are coupled using the incompressible ideal-gas model that determines density as a function of temperature for a constant pressure. The evapo-transpiration model for the crop is taken into account in the solver as source terms for the equations of energy and water vapour concentration. One can refer to Boulard and Wang (2002) for the details of this coupling which has been introduced in the CFD resolution using specific routines (User Defined File). In addition, the standard k-ε model has been selected to model the turbulence effects in the airflow. A specific routine (User Defined File) has been specially developed to take into account the sources terms of spores in specific zones, these sources terms being either positive (source) or negative (sink). Thus, the global set of solved variables is: momentum components, pressure, turbulent energy, dissipation rate of turbulent energy, air temperature, air humidity and air concentration of spores in the domain. In addition, new intermediate variables of great scientific interest can also be computed: the leaves surface temperature and humidity, their transpiration, the deposition of spores on the leaves and the soil surface.

2. The domain model

The boundary conditions and the meshing of the 2D domain are presented on figures 1 and 2. The domain is 40 m wide and 15 m high. The greenhouse is made up of four 5.4 m high and 7 m wide spans with roof vents. The aperture of the roof vents has been adjusted to fix values. The left span is equipped with a 1 m high side opening (aperture = 24%) and the right span is separated from the others and serves as passageway. The rose crop is located in the three left spans and is modelled with a 1.7 m high and 20 m wide rectangle (Fig. 1). In the whole volume of this rectangle, source or sink terms for the porous medium, energy balance and spores impaction and deposition are activated. Insect-proof nets are located in each aperture and are modelled with thin rectangles in the openings. Source terms for porous medium and for spore’s impaction are activated in these rectangles. Several grids have been tested in order to insure the independence of the results to the density of mesh and a 50.000 cells grid has been chosen. Note that the grid is more refined in vicinity of the openings were the gradients are expected to be important (Fig. 2).

The inlet velocity profile (Fig. 1) linked to the left boundary of the domain has been deduced from experimental measurements (Haxaire, 1999) and is defined as:

$$u = \frac{u_*}{K} ln(\frac{z}{z_0})$$

with u_* the friction velocity ($u_*=0.28ms^{-1}$) ; K the Von Karman constant ($K=0.41$) and z_0 the friction length ($z_0=0.0193m$). The turbulent kinetic energy and the turbulent dissipation rate are described by the following expressions (Hoxey and Richardson ,1993) :

$k=\frac{u_*^2}{\sqrt{C_\mu}}$ and $\varepsilon=\frac{u_*^3}{K(z+z_0)}$ with $C_\mu=0.09$

3. The model of spores' transport

A classical Eulerian model (Dupont et al., 2006) allows for the determination of the concentration of spores C in the whole domain. The equation of transport is used with the taking into account of the sedimentation velocity of spores v_s *i.e.* the slip velocity due to the gravity effects ($v_s=3.10^{-3}\ m\ s^{-1}$ for a spore's mean diameter of 10^{-5} m*)*. This equation becomes, for turbulent steady state conditions and for the mean value of the concentration of spores $\overline{C}$ (Foudhil, 2002):

$$u_j\frac{\partial\overline{C}}{\partial x_j}-v_s\frac{\partial\overline{C}}{\partial x_j}\delta_{j3}=-\frac{\partial}{\partial x_j}\left(-\frac{\nu_t}{\sigma_c}\frac{\partial\overline{C}}{\partial x_j}\right)+S_p$$

with δ_{j3} the Kronecker's symbol, ($\delta_{j3}=1$ in the vertical direction); σ_c the turbulent Schmidt number ($\sigma_c=0.5$) and S_p the source term. Three zones are considered for the description of the source term: the ground, the crop and the insect-proof nets, each of them having a specific behaviour.

The source term for the ground stands for the deposition flux of spores on the ground S_d and can be written as:

$$S_d=v_d.\overline{C}$$

Knowing v_s the sedimentation velocity, one can deduce v_d the deposition velocity with the relation (Stenfeld and Pandis, 1998):

$$v_d=v_s+\frac{1}{r_a}$$

With r_a the aerodynamic resistance in the ground boundary layer. This quantity is determined with the velocity profile and can be expressed as:

$$r_a=\frac{1}{Ku_*}ln\left(\frac{z}{z_0}\right)$$

The source term for the crop must take into account two quantities: the sedimentation flux S_s on leaves surfaces and the collecting flux of spores by impact on stems and leaves S_i. These terms are defined as:

$$S_s=-E_s v_d\overline{C}LAI_v\cos\alpha$$

$$S_i=-E_i\left\|\vec{U}\right\|\overline{C}LAI_v\cos\alpha$$

With E_s and E_i the sedimentation and impact efficiencies, LAI_v the leaf array index per volume unit and α the mean slope angle of leaves to the horizontal. The sedimentation phenomenon is generally considered as optimal, so E_s is equal to 1 and the impact efficiency is defined as:

$$E_i=\frac{0.86}{1+0.442St^{-1.967}}$$

With St the Stokes number defined as:

$$St = \frac{v_s \left\| \vec{U} \right\|}{gL}$$

L is a characteristic length (diameter of stems or length of leaves)

The source term for the insect-proof nets only takes into account the impact effect and the impact efficiency was experimentally defined in a wind tunnel (Boulard *et al.,* 2007). Results lead to an experimental value $E_i=0.56$ for a 59% porosity net.

RESULTS AND DISCUSSION

Simulations were performed in order to determine the distribution of relevant variables to the climatic conditions such temperature, mass fraction of water vapour and concentration of spores within the greenhouse air and spores deposition within the crop.

For validation, these results were compared to experimental data obtained in a greenhouse where climate conditions, spore concentration and spore deposition were sensed for performing a global greenhouse spore's balance (Boulard *et al*, 2007). The average outside climate and spore's concentration sensed during the diurnal period were used as boundary conditions for two different days (days n° 105 and 125 of 2004) and we have compared our simulations (we shall only present a comparison for the day n° 125) with measured data for greenhouse air exchange rate and inside climate and spore's concentration and deposition.

1. Model validation

Experimental data of a parallel study aiming at the determination of the origin of the Botrytis inoculum for the same rose greenhouse were used for validating the model; their corresponding boundary conditions are presented in Table 1. Five parameters have been selected for comparing measured and simulated data: the ΔT between inside (at the centre of the greenhouse) and the outside, the Δ absolute air humidity at the same positions, the global air exchange rate determined by integrating the air fluxes at the openings, the inside spore's concentration in the air and the deposition on the crop cover at the center of the greenhouse.

As already demonstrated in previous greenhouse CFD simulations (Reichrath and Davies, 2002), examination of the results (Table 2) shows that the predictions of the flow transfer and inside climate conditions are very accurate, even as it is the case here, for a greenhouse with a crop cover inside. Thus, it confirms the soundness of the coupling model between aerial transfers and crop functioning. However, the novelty of the study lies principally in the modelling of the spore's transfers and one can also state a very close correspondence between measured and simulated values concerning both the inside spore's concentration in the centre of the greenhouse and spore's deposition on the crop cover (Table 2). The spore's concentration in the middle of the second span has been computed from the simulation results and is equal to 1.17 spore's m^{-3} whereas the measured value for the concentration is 1.19 spores m^{-3}. The computed flux of captured spores by the crop cover and the inner ground is equal to 65000 spores for 12h whereas the measured one using Petri boxes in the centre of the greenhouse is equal to 85000 spores for 12h.

Other values for the day n° 105 (not presented here) are also in close correspondence and confirm the soundness of the simulation for various boundary conditions.

2. The climatic parameters

The temperature distribution within the domain is presented in Fig.3. The effect of the ventilation is clearly showed: a 5 K difference is found between the left span and the third span because of air flowing in through the side vent and exiting through the roof vents. The distribution of the concentration of water vapour within the whole domain (Fig.4) and within the crop presents the same pattern than temperature's ones. Consequently the water content varies from 10 g/kg outside to 12 g/kg in the left span and 14 g/kg in the third span.

3. The concentration of spores

The concentration of spores within the whole domain is presented in Fig.5. For the outdoor part of the domain, the concentration of spores has been set up to 6.5 spores m^{-3} and is homogeneous, expect in the vicinity of the ground where the concentration is divided by 2. Hence the concentration flowing in the left span through the side vent is reduced to 3.3 spores m^{-3} directly after the screen, 1.2 spores m^{-3} in the middle of the left span and only 1 spore in the right span. These values confirm the correct computation of the source term for the screens which takes into account an impact efficiency of the screen $E_i=0.56$. From the left span to the third span, the concentration of spores is reduced from 3.3 to 1 spore's m^{-3} under the effects of impact and sedimentation within the crop. The flux of captured spores per volume unit within the crop is presented in Fig.6. It decreases from 5 10^{-3} to 1 10^{-3} spores m^{-3} s^{-1}, this diminution being linked to both concentration and velocity decrease from the left to the right of the crop.

CONCLUSION

The Fluent CFD code has been used to develop a global and distributed CFD model of climate and biotic particles transfer in a greenhouse. It is especially based on the coupling between aerial flow and crop functioning and on the use of an Eulerian model for the simulation of the concentration of spores of *Botrytis cinerea* within a greenhouse equipped with insect-proof screens. Experimental validation of the numerical results for the aerial transfers and climatic conditions confirms the soundness of the CFD approach completed with a coupling between aerial transfers and crop sensible and latent heat exchanges. The experimental validation of the numerical results for inside concentration of spores shows the fair modeling of the different source terms used for the screens and for the crop. Comparisons with experimental values show both a good agreement for the inner concentration and for the flux of captured spores. In the future, extensions of this work using a 3D model should improve its validation.

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Notations

C : concentration of spores, sp. m^{-3}
$\overline{C}$: mean concentration of spores, sp. m^{-3}
C_i : inlet concentration of spores, sp. m^{-3}
C_μ : constant for the k-ε model
E_i : impact efficiency
E_i : sedimentation efficiency
g : acceleration of gravity, m s^{-2}
k : turbulent energy, m^2 s^{-2}
K : Von Karman constant
L : characteristic length, m
LAI_v : leaf array index per volume unit, m^{-1}
r_a : aerodynamic resistance, s m^{-1}
S_d : source term for deposition, sp. m^{-2} s^{-1}
S_i : source term for impact, sp. m^{-2} s^{-1}
S_p : global source term, sp. m^{-2} s^{-1}
S_s : source term / sedimentation, sp. m^{-2} s^{-1}
St : Stokes number
u : inlet wind velocity, m s^{-1}
u_* : friction velocity, m s^{-1}
$\|\vec{U}\|$: velocity modulus, m s^{-1}
v_d : deposition velocity, m s^{-1}
v_s : sedimentation velocity, m s^{-1}
z : vertical coordinate, m
z_0 : friction length, m
α : angle, degree
δ_{ij} : Kronecker's symbol
ε : turbulent dissipation rate of k, m^2 s^{-3}
ν_t : turbulent cinematic viscosity, m^2 s^{-1}

TABLES

Temperature [°C]	14
Absolute Humidity [kg/kg]	0.010
Global Radiation [W/m2]	164
Wind speed [m/s]	1.81
Outside spores concentration [sp]	6.5
East roof vent opening [%]	12
Side vent opening [%]	24

Table 1: Outside boundary conditions for the day n° 125 (average values measured over the 8h-20h period)

Parameters	Measured	Simulated
ΔTemperature (inside-outside) [K]	6.43	6.65
ΔAbsolute Humidity (inside-outside) [Kg/Kg]	0.004	0.0028
Ventilation rate [m^3/s]	1.23	1.08
Ci [sp/m^3]	1.17	1.19
Ss [sp/12hours]	85000	65000

Table 2: Comparison of experimental vs. simulated values of the greenhouse climate and spores concentration and deposition in the centre of the greenhouse (day n° 125, average values over the 8-20h period)

FIGURES

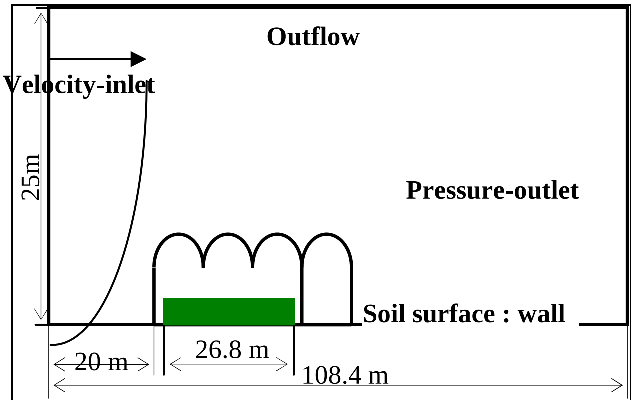

Fig.1: Scheme of the domain (108 mx25m) and of its boundary conditions.

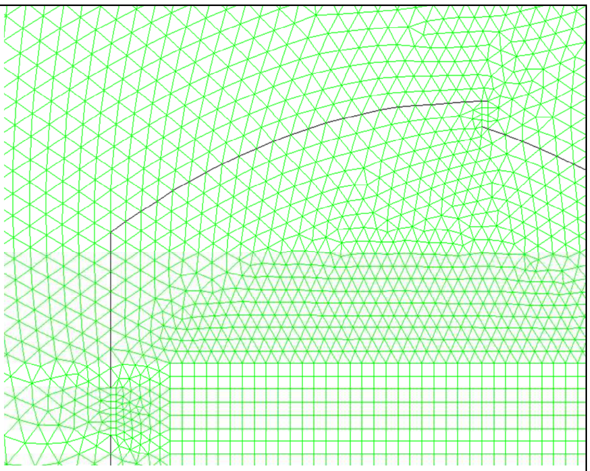

Fig.2: Detail of the meshing of the domain.

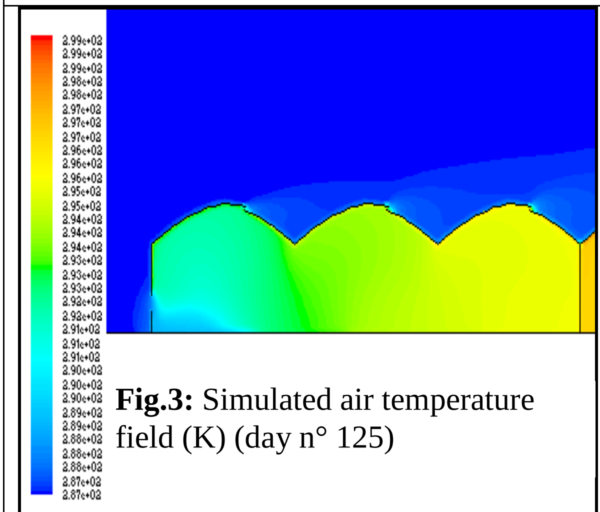

Fig.3: Simulated air temperature field (K) (day n° 125)

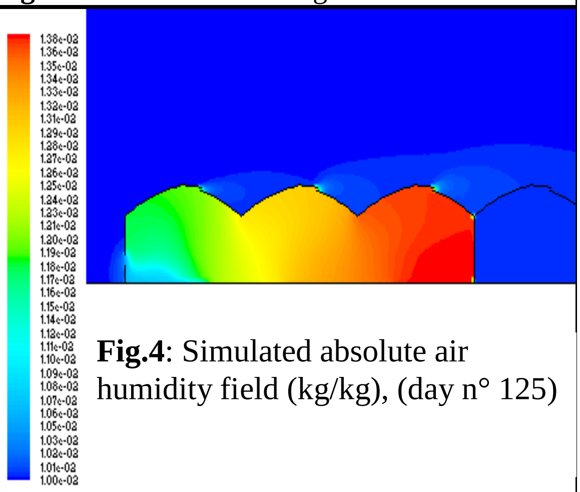

Fig.4: Simulated absolute air humidity field (kg/kg), (day n° 125)

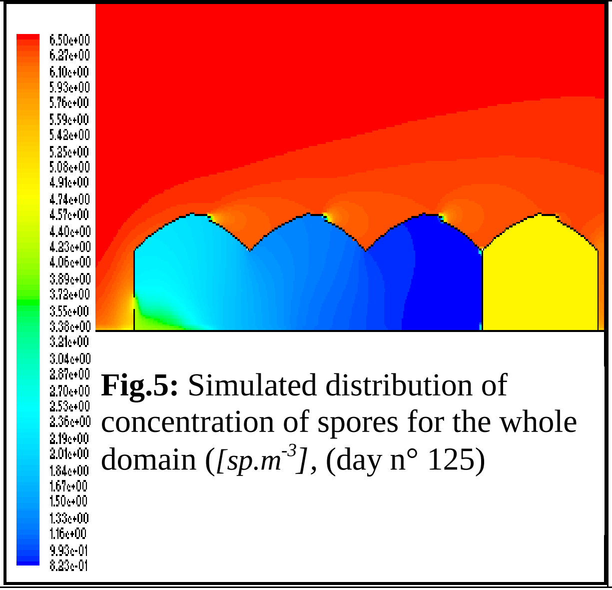

Fig.5: Simulated distribution of concentration of spores for the whole domain (*[sp.m^{-3}]*, (day n° 125)

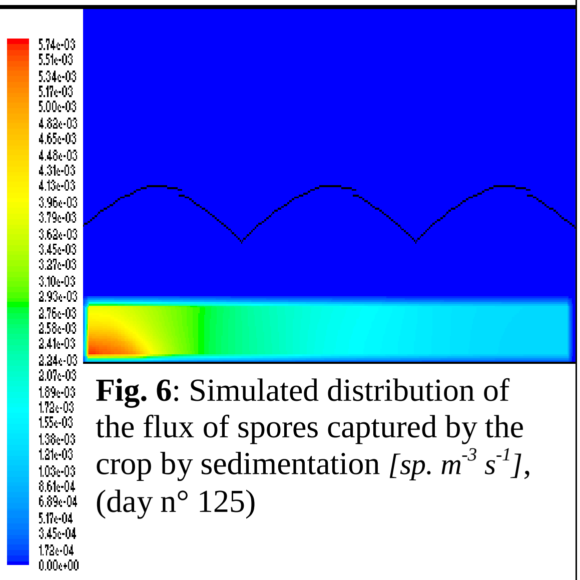

Fig. 6: Simulated distribution of the flux of spores captured by the crop by sedimentation *[sp. m^{-3} s^{-1}]*, (day n° 125)