CFD Prediction of the Distribution and Deposition of Fungal Spores in a Greenhouse

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Abstract

The scope of this paper is the description of a specific module associated to a conventional Computational Fluid Dynamics model and developed to compute the effects of soil, insect-proof nets and vegetation rows on the deposition of Botrytis spores, i.e. spores with a mean diameter of ten micrometers. The objective of this work is aimed at the simulation of the spore 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. The specific model consists in the determination of sink terms in the equation of transport of a scalar that corresponds to the particle concentration in the airflow. Three kinds of sink terms are considered for the soil, for the insect-proof nets and for the vegetation rows.

The necessary parameters for the parameterisation of the model together with the spore concentration and climate boundary conditions were determined in an experimental study for a rose greenhouse with roof and lateral vents equipped with insect-proof nets, which is presented in a companion paper (Boulard *et al.*, 2006). The effect of the crop rows explains the heterogeneity of concentration in the crop and in its vicinity. The influence of the soil is limited to a thin boundary layer far from the greenhouse that grows windward of the greenhouse near the lateral vents.

INTRODUCTION

Computational Fluid Dynamics constitutes nowadays a powerful tool for the determination of the climatic parameters prevailing in a greenhouse system. From several years, some authors have presented a wide range of studies devoted to the modeling and simulation of different greenhouse configurations and different climatic input conditions (Reichrath and Davies, 2002). More recently, the development of the use of insect-proof screens in greenhouse vents has led to the taking into account of the influence of these equipments on the ventilation rate and therefore on the distribution of the climatic parameters (Fatnassi *et al.*, 2003). From an agronomic point of view (Quinn *et al.*, 2001), the determination of the prediction of the concentration pattern of pollutants or biotic materials is of big interest, especially for the determination of the concentration of spores transported by wind and deposited on or removed from leaves surfaces in greenhouse crops. For that purpose, the simulation of the concentration of spores can be achieved with an Eulerian model that describes the transport of a scalar (the concentration of spores) in the domain of interest (the greenhouse and its direct environment). The boundary conditions must be accurately defined for the deposition rate of spores on the greenhouse soil and for the interception rate of spores by the insect-proof screens located in the greenhouse vents. The influence of the crop, considered as a porous medium for the momentum equation, is taken into account by using the impaction rate of spores on the plant.

This paper presents the first results of 2D numerical simulations performed with the Fluent CFD code for a multi span greenhouse with roof vents and a side opening both equipped with insect-proof nets. Experimental studies (Chave *et al.*, 2004; Boulard *et al.*, 2006) relating to these facilities have been carried out in order to determine the balance of *Botrytis cinerea* spores. More particularly, this study aims at the validation of the modeling of deposition of spores on the soil and of interception of spores within the crop.

METHODS

The CFD Code

The CFD code Fluent v. 6.1. has been used to perform the simulations of the flow in the greenhouse. The low velocity fields encountered for air flowing through the greenhouse require the taking into account of free convection effects.. Hence, the determination of temperature and humidity fields within the greenhouse 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 (Roy and Boulard, 2004) and the standard k-ε model has been selected to model the turbulence effects in the airflow. Therefore, the solved variables are: momentum components, pressure, turbulent energy, dissipation rate of turbulent energy, temperature, humidity and the concentration of spores in the domain. A specific routine (User Defined File) has been specially developed to take into account the source terms of spores in specific zones. Note that source terms can be positive (source) or negative (sink).

The domain model

The meshing of the 2D domain is presented on figure1. 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 12%. 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 crop is located in the three left spans and is modelled with a 1.7 m high and 20 m wide rectangle. The source or sink terms for the porous medium, energy balance and spores impaction and deposition are activated in this rectangle. Insect-proof nets are located in each aperture and are modelled with thin rectangles in the openings. Source terms for porous medium and for spores impaction are activated in these rectangles. Several grids have been tested in order to insure the independence of the results to the density of the mesh and a 50.000 cells grid has been chosen. Note that the grid is more refined in the vicinity of the openings where the gradients are expected to be important. The inlet velocity profile 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 $C_\mu=0.09$

The model of transport of spores

The classical Eulerian model 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 the 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:

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

With v_s the sedimentation velocity and v_d the deposition velocity (Stenfeld and Pandis, 1998) which can be determined with the relation:

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

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

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

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

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

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

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:

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

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.*, 2006). Results lead to an experimental value $E_i=0.56$ for a 59% solidity 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 and within the crop. The previously defined logarithmic velocity profile is applied to the left boundary of the domain ($u = 2.7\ m\ s^{-1}$ for $z = 1\ m$; $u = 3.8\ m\ s^{-1}$ for $z = 5\ m$). Inlet temperature and mass fraction of water vapour are constant ($T_i = 287\ K$; $r_i = 9.56\ 10^{-3}\ kg\ kg^{-1}$; $Rh = 96\%$); the global density of radiation within the greenhouse is set to $R_{gi} = 300\ W\ m^{-2}$ and the inlet concentration of spores is $C_i = 6\ spores\ m^{-3}$.

The climatic parameters

The temperature distribution within the domain is presented in Fig.2. The effect of the ventilation is clearly shown: a 3 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. In the right span, which includes only a roof vent, a weaker air circulation is set up and the temperature is 7 K higher than the outside temperature. The distribution of temperature within the crop is presented in Fig.3. The left side of the crop is highly coupled with the ventilation flow while the upper side which is directly exposed to the sun radiation and the right side, where the ventilation flow is low, are up to 4 K warmer than the surrounding air. The distribution of the concentration of water vapour within the whole domain (Fig.4) and within the crop presents the same patterns than temperature’s ones. Consequently, the relative humidity varies from 90% in the third span to 96% in the left span.

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 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 about 4.5 spores m^{-3} and is reduced to 2 spores m^{-3} directly after the screen. 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 2 to 0.33 spores 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 2.9 10^{-2} to 5 10^{-3} spores m^{-3} s^{-1}, the diminution being linked to both concentration and velocity diminution from the left to the right of the crop.

The mean concentration of spores within the three left spans has been computed from the simulation results and is equal to 1.13 spores m^{-2} and the concentration within the crop is 1.05 spores m^{-3}. Comparatively, the mean experimental value for the concentration within the crop is 0.8 spores m^{-3} (Boulard *et al.*,2006). The computed flux of captured spores by both the crop and the inner ground is equal to 19.75 spores s^{-1}. This value is high when compared with experimental values that vary from 1.4 to 2.9 spores s^{-1}. This discrepancy is mainly related to the differences between the ventilation rate for the simulation and for the experiments. Consequently, the determination of the velocity field of the wind would be of big interest together with the measurements of concentration within the greenhouse.

CONCLUSION

The Fluent CFD code has been used to develop an Eulerian model for the simulation of the concentration of spores of *botrytis cinerea* within a greenhouse equipped with insect-proof screens. The taking into account of free convection effects has led to the use of an active crop model for the determination of the velocity, temperature and humidity patterns in the domain of interest. Numerical results for the concentration of spores show the correct modeling of the source terms for the screens and for the crop. Comparisons with experimental values show a good accord for the inner concentration but an important discrepancy for the flux of captured spores. Thus, a fine experimental determination of the climatic conditions within the greenhouse together with a 3D model will permit to improve the validation of the model.

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Notation

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}
r_i : mass fraction of water vapour, kg kg^{-1}
R_{gi} : global density of radiation, W m^{-2}
Rh : relative humidity
S_p : global source term, sp. m^{-2} s^{-1}
S_s : source term for sedimentation, sp. m^{-2} s^{-1}
St : Stokes number
T_i : inlet temperature, K
u : inlet wind velocity, m s^{-1}
u_* : friction velocity, m s^{-1}
$\left\|\vec{U}\right\|$: 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}

S_d : source term for deposition, sp. m^{-2} s^{-1}
S_i : source term for impact, sp. m^{-2} s^{-1}
ν_t : turbulent cinematic viscosity, m^2 s^{-1}
σ_c : turbulent Schmidt number

Figures

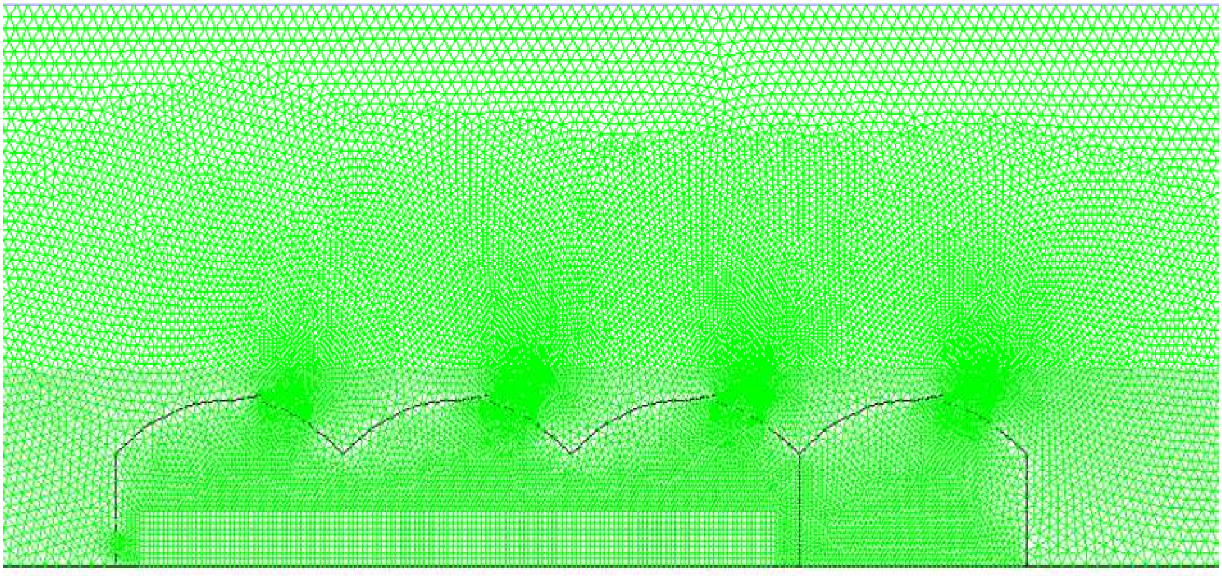

Fig.1: Mesh of the domain

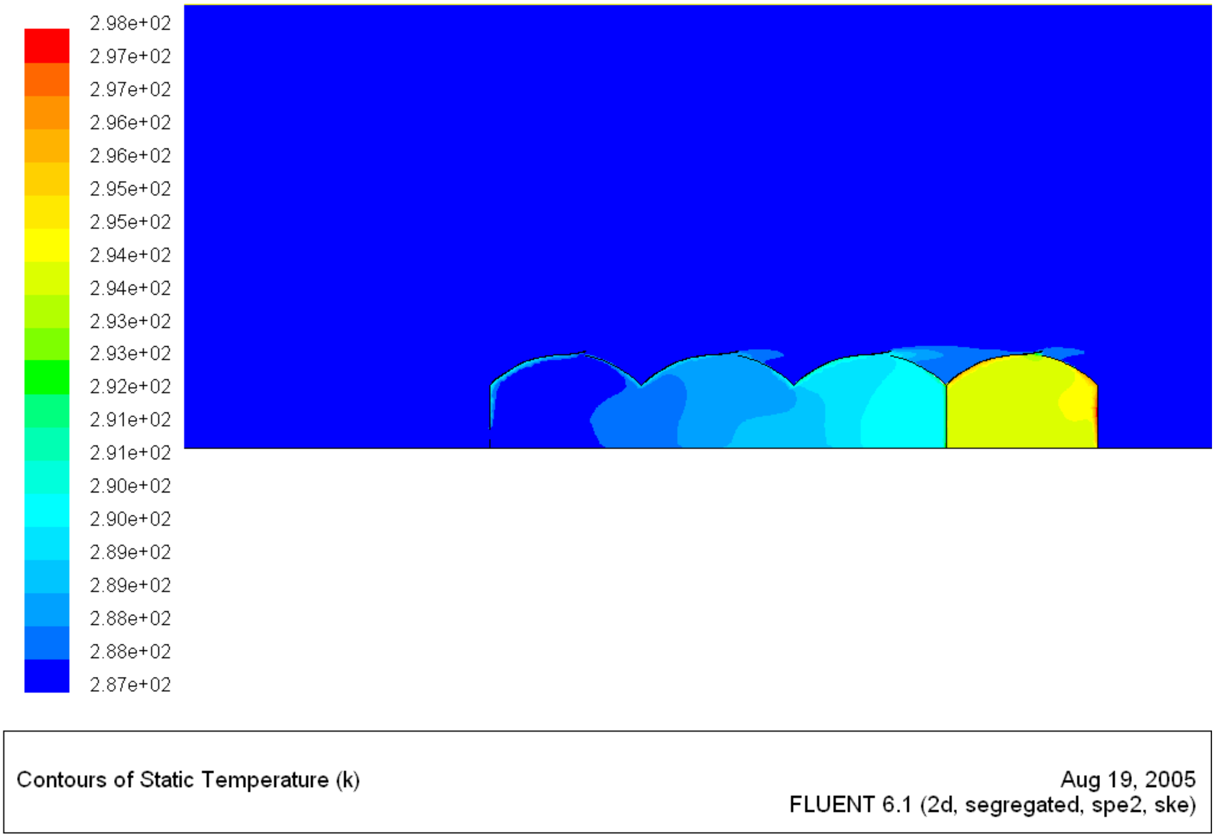

Fig.2: Simulated temperature distribution for the whole domain

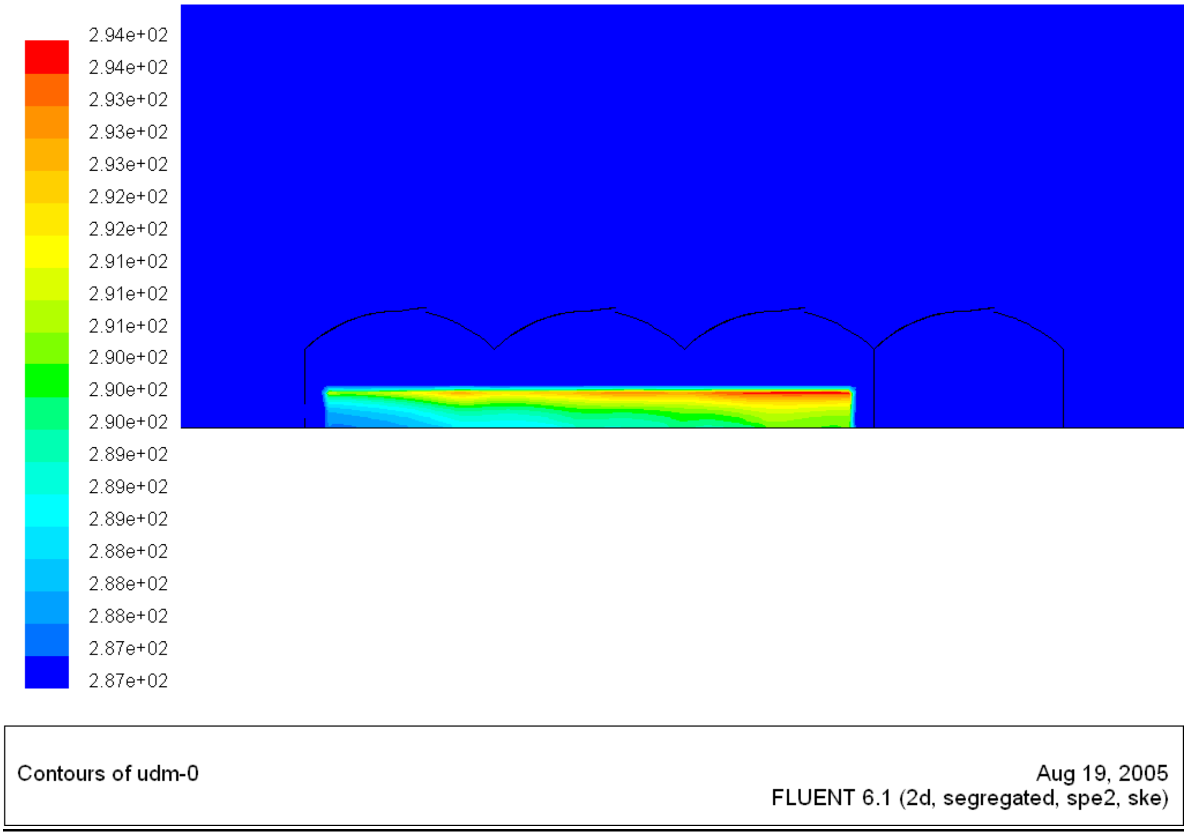

Fig.3: Simulated temperature distribution in the crop

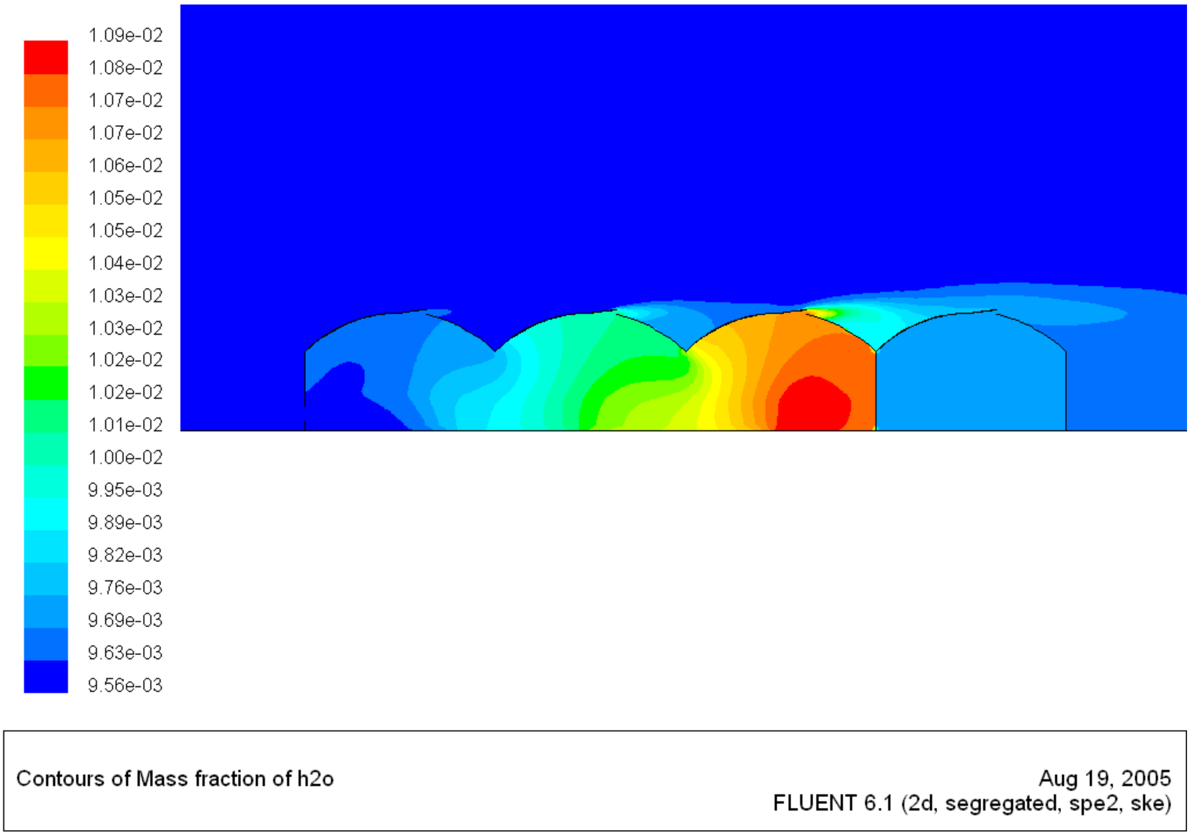

Fig.4: Simulated mass fraction of water vapour distribution for the whole domain

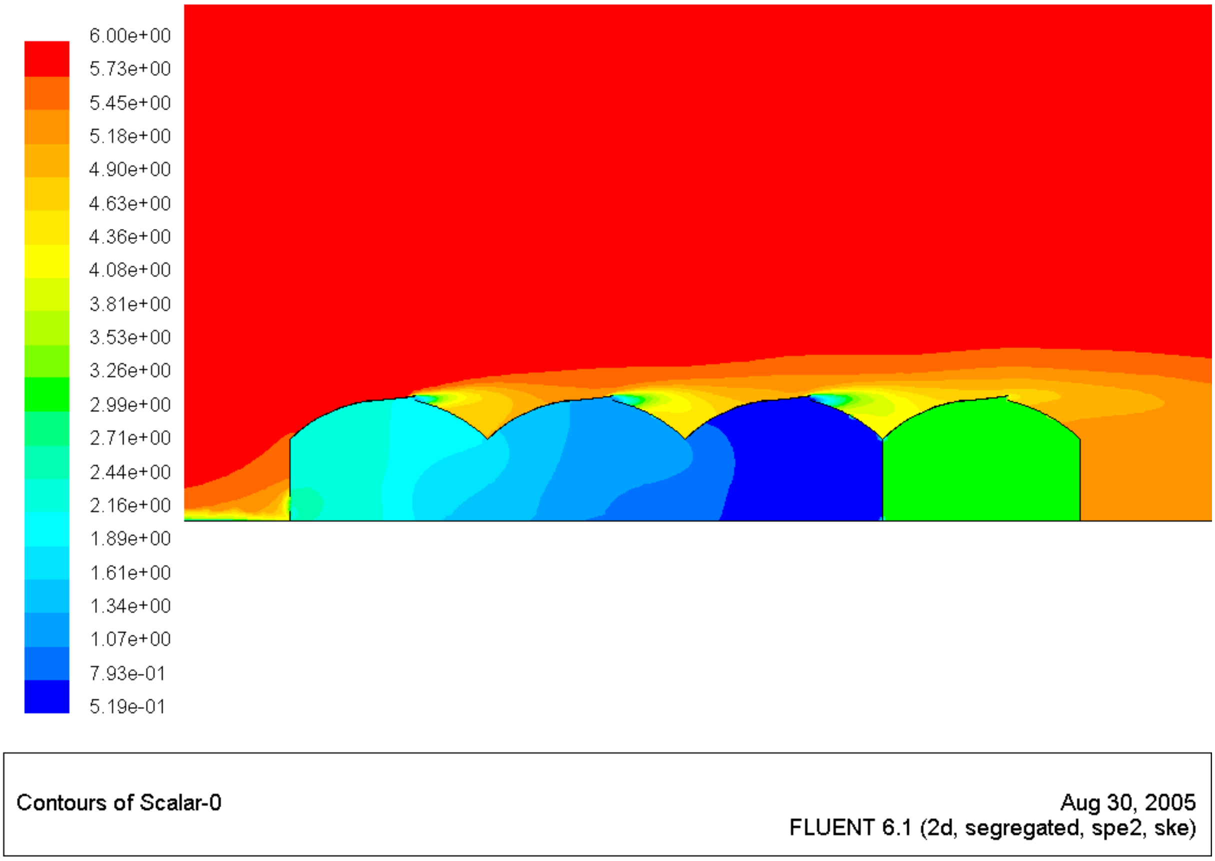

Fig.5: Simulated distribution of concentration of spores for the whole domain

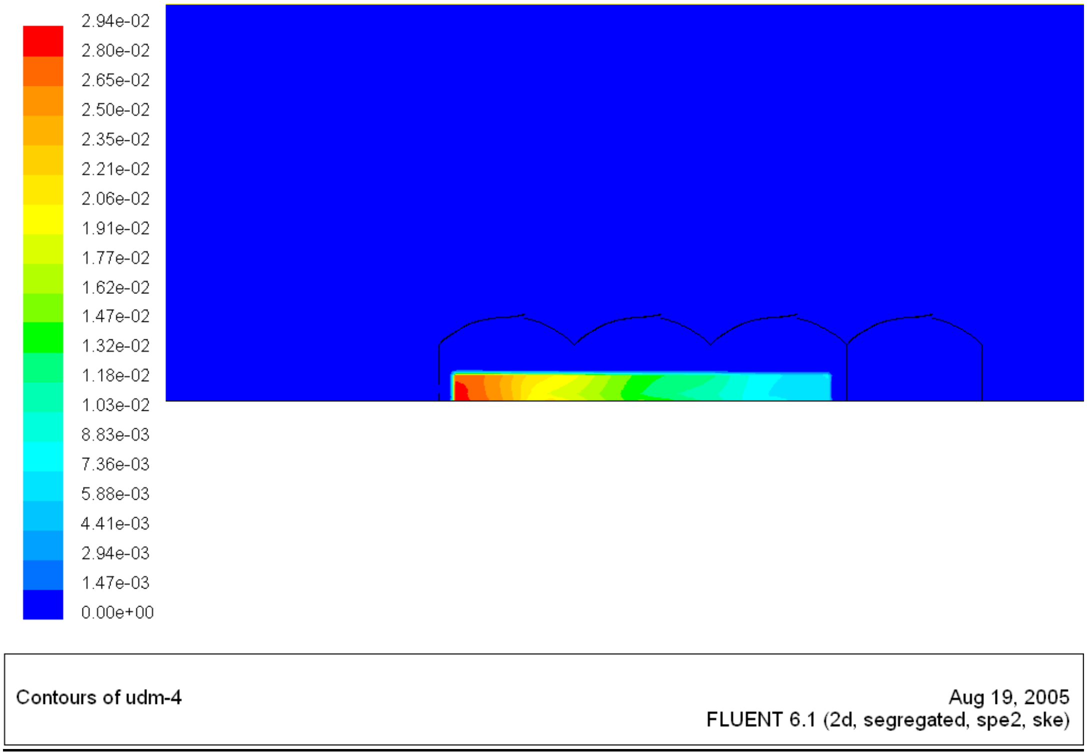

Fig.6: Simulated distribution of the flux of captured spores for the crop