CFD Prediction of the Natural Ventilation in a Tunnel-Type Greenhouse: Influence of Wind Direction and Sensibility to Turbulence Models

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Abstract

A contribution to the development of a new model for the characterisation of the climatic conditions in a tunnel-type greenhouse is presented, which takes into account the crop (tomato) like an active 3D region where both the momentum transfer (porous media) and the heat and humidity transfers between the crop and the inside airflow are considered. The effects of the wind direction on the climatic parameters inside the greenhouse are simulated together with the use of different turbulence models available in the CFD code.

The model consists in the determination for each node of the crop grid of the energy balance between the transpiration flux and the radiation flux. The heat and humidity transfer coefficients are deduced from the leaf laminar boundary layer characteristics which are calculated with the local velocity of air in the crop. This model is included in the Fluent® CFD package in the form of a User Defined File (UDF) added to the main processing unit. The 3D geometry includes a tunnel-type greenhouse with five vents on each side and a five rows mature tomato crop and its external direct environment. The wind boundary conditions for the velocity distribution are deduced from experimental data and the direction of the wind, relative to the longitudinal axis of the greenhouse, can vary from 0 to 90 degrees. Three turbulences model are tested: the standard k-ε model, the renormalisation group (RNG) model and the realizable k-ε model.

The results of the simulations performed for 0, 45 and 90 degrees show clearly the influence of the direction of the wind direction on the velocity, temperature and humidity distributions inside the greenhouse. The computations of the velocity field using the different turbulence models also show noticeable difference in the velocity, temperature and humidity patterns inside the greenhouse and confirm the importance of the choice of the closure model for the modelling of turbulence.

INTRODUCTION

Computational fluid dynamics (CFD) packages are nowadays powerful tools for modelling of airflows and climate patterns in agricultural structures like greenhouses. Simulations with CFD allow determining the influence of the greenhouse design parameters like orientation relative to wind direction and location of the ventilators, on different climatic parameters like temperature and humidity distributions, ventilation flow rate, etc...The use of CFD is to date the only way of approaching the distributed climate in a greenhouse and in the inner crop by resolving the equations of heat and mass transfer for an accurate mesh of discrete locations (Boulard et al., 2002-1). Furthermore, the perfecting of these predictions, especially for relative humidity, constitutes a decisive contribution to the integrated pest management (IPM) (Boulard et al., 2002-2).

Since about twenty years, some authors have performed experimental studies relative to the effects of the natural ventilation on the crop transpiration (Bot, 1983; De Jong, 1990; Fernandez and Bailey, 1992; Boulard et al., 1996). At the same time several authors have developed global air exchange models based on the “big leaf” assumption (Stanghellini, 1987; Yang et al., 1990; Boulard and Wang, 2000) and energy balance methods (Kindelan, 1980; De Halleux et al., 1991; Wang and Deltour, 1996).All these studies about global models are summarized in a recent review paper (Roy et al., 2002-1).

With regard to numerical simulations, some authors have been used commercial or self-developed CFD codes to perform simulations of different greenhouse configurations. From these studies, summarized in a review paper by Reichrath and Davies (2002), it can be deduced that the use of a 3D model and the taking into account of the inner vegetation are two essential points for the consistency of the numerical results. In a previous paper (Roy et al, 2002-2) we presented a model that combines different scales of a 3D model (the tunnel an its direct environment; the inner domain of the tunnel) and that takes into account an active crop by modelling the crop as a porous medium and determining the heat and water vapour exchanges at the crop level. This model has been recently adapted to the Fluent® code and the airflow, temperature and humidity patterns in a tunnel-type greenhouse have been determined in order to analyse the influence of both the boundary conditions (wind direction) and the sensibility to the turbulence model.

METHODS

The Principles of the CFD Code

The finite volumes numerical scheme is used by the Fluent® code to solve the equations of conservation for the different transported quantities in the flow (mass, momentum, energy, water vapour concentration). The domain of interest is first meshed with the Gambit® meshing tool according to a 3D grid that generates a finite number of elementary volumes. Consequently, the spatial discretisation of the domain enables the use of the finite differences method to solve the discretised conservation equations. These equations are combined with the boundary conditions and solved with the SIMPLE algorithm. This code first performs the coupled resolution of the pressure and velocity fields and then the others parameters, like temperature or water vapour concentration (Fluent® user’s guide, 2001). Special items like the mechanical or climatic behaviour of the rows of tomato crop are determined using a customisation, i.e. a routine included in a user defined file (UDF) and built for the determination of the parameters exclusively relevant to the vegetation.

The Domain Model

The domain of interest takes into account the plastic tunnel (22 m × 8 m × 3 m) which includes ten side vents regularly located along both sides of the tunnel and eight rows of mature tomato crop: two single rows and three double rows (Fig.1).The boundaries of the direct external environment are sketched on Fig. 2. The size this domain (82 m long, 68 m wide and 24 m high) was chosen large enough and tested in order to insure the independence of airflow’s behaviour to the boundaries locations. A logarithmic inlet wind velocity profile (atmospheric boundary layer model) was considered and deduced from experimental values (Haxaire, 1999). The angle of incidence between the inlet velocity vectors and the lengthwise axis of the tunnel can vary from 0 to 90 degrees. The temperature of the inlet wind is fixed and a constant heat flux density is applied on the inner floor to simulate the radiation absorption in the tunnel and it exchanges with the inner airflow (mixed convection).

The meshing of the domain was determined with two characteristic sizes: 0.15 m meshes inside the tunnel and 1 m meshes outside. Consequently, two structured meshes have been defined and connected together with an unstructured mesh (Fig.3). The grid is more refined near the floor and near the walls and the vents of the tunnel where strong velocity gradients are supposed to be found. The choice of this grid was validated after several trials in order to both optimise the computational time and the precision of the model, especially in the vents and in the crop.

The Crop Model.

The presence of a crop in the greenhouse gives rise to a sink of momentum due to the friction forces (drag forces) on the leaves. The dynamic behaviour of the crop is assimilated to a porous medium and the Darcy-Forchheimer model restricted to its inertial terms is applied to determine the pressure drop in the porous medium (Boulard and Wang, 2002). This pressure drop is then taken into account in the momentum equation as a source term S_v. The values of the drag coefficient C_d, and the leaf area density L_{ad} have been experimentally determined by Haxaire (1999) for a mature tomato crop and are presented in Table 1. The model of crop transpiration is considered by means of the heat and water vapour transfers between the leaves and the air. Consequently two variables, the leaf temperature T_l and the absolute humidity of the leaf w_l, which are not determined in the whole inner space must also be computed in the crop volume. The aerodynamic resistance r_a is determined from the laminar boundary layer theory (Schlichting, 1974) using the computed air velocity in each node of the crop volume mesh, and the stomatal resistance r_s is considered as a function of both the global radiation density R_g and the vapour pressure deficit D_a (Boulard et al., 1991). The formulae linking these parameters and allowing for the determination of T_l and w_l are presented in Table 2.

The Customisation of the CFD Software.

The crop model is taken into account in the solver as source terms added to the equations of momentum (porous medium) and the equations of energy and concentration (heat and mass balance). These source terms are computed at each iteration step for each node of the crop by a C language routine that runs the determinations of T_l, w_l together with the transpiration density flux ϕ_w.

The turbulence models

Three turbulence models available from the Fluent® package have been evaluated in this study: the standard k-ε model, the renormalisation group (RNG) model and the realizable model. These semi empirical models imply the solving of two supplementary conservation equations relative to the turbulent kinetic energy k and to its dissipation rate ε. When comparing with the standard model, the RNG model takes into account additional term in the ε equation and the turbulent Prandtl number is determined with an analytical formula instead of a user-specified constant value. The realizable model also contains a different formulation for the ε equation and the turbulent viscosity is determined with a non constant C_μ coefficient, unlike the two others models which use constant values.

RESULTS AND DISCUSSION

Influence of the wind direction

Three wind directions were tested with respect to the lengthwise axis of the tunnel: 0; 45 and 90 degrees. The inlet velocity profile (logarithmic), the inlet temperature (298 K), the water vapour concentration (0.01 kg_{water} kg_{air}^{-1}) and the turbulence model (standard k-ε) were unchanged for each wind direction. The climatic conditions prevailing in a significant transverse plane have been determined and presented. This vertical plane is located in the first opening plane of the tunnel (vent # 1 on Fig. 2). In Fig.4 the temperature distribution along a 1 m high line is presented. The differences are clearly shown: temperature is 5 K higher for 0° incidence wind in the center of the tunnel when compared with the 90° incidence distribution. Differences between 45° and 90° incidences are weaker: less than 1 K in the center of the tunnel. Such differences are also present in the humidity distribution for a 1 m high line (Fig. 5): relative humidity is quite 20% higher for 0° incidence when compared with the 90° incidence distribution and less than 5% difference between 45° and 90° incidences. These distributions clearly show the influence of the wind conditions: the inner climate is quite coupled with external conditions for 90° wind incidence when inside climatic parameters are quite different from external conditions for 0° wind incidence. The velocity distribution along a 1 m high line is presented on Fig. 6. The velocity of air flowing in the tunnel through the left vent greatly depends on the wind direction: velocity magnitude vary from 0.2 m s^{-1} for 0° incidence to 1.5 m s^{-1} for 90° incidence. The temperature distribution in the crop rows is presented on Fig.7 for 45° incidence: temperature is higher near the upper side of the rows where the radiation flux is high. Temperature decreases in the rows and near the left vent where air flows in the tunnel. In this part of the crop the temperature is 2 K lower than external conditions because of the intensity of the evaporation flux promoted by convective transfers between the airflow and the crop. .

Influence of the turbulence model

In order to compare the influence of the turbulence models on numerical results, simulations have been performed with 0° wind incidence for each turbulence model. Velocity fields in the transverse vertical plane located in vent # 1 are presented on Fig. 8 and 9 for standard k-ε model and RNG model. The magnitude of the velocity is quite different in the center of the tunnel, especially on each side of the central row where velocity is lower than 0.1 m s^{-1} with the standard k-ε model and lower than 0.2 m s^{-1} with the RNG model. Note that for 0° wind incidence, air flows out through the first vents (# 1 on Fig. 2) and flows in through the other vents (Haxaire, 1999). The velocity distribution along a 1 m high line is presented on Fig. 10 for the three turbulence models. The distributions are similar excepted on each side of the central row where the taking into account of the standard k-ε model leads to an underestimation of the velocity when compared with both other models. The temperature distribution along a 1 m high line is presented on Fig. 10 for the three turbulence models. The distribution is quite homogeneous with the RNG model where the difference is lower than 0.5 K. This heterogeneity increases with the realizable model and reaches 2 K with the standard k-ε model. The homogeneity of the temperature distribution is related to the mixing capacity of the velocity field. The taking into account of the RNG model leads to the determination of well developed vortex structures close to the central row; hence the climatic conditions prevailing in the tunnel are more homogeneous when compared to those determined with both other models.

CONCLUSION

The Fluent® CFD code has been used for the determination of the influence of the wind direction on the inner climate distribution in a tunnel-type greenhouse. An active crop model has been developed to simulate the heat and water vapour transfers between the crop and the ventilation airflow. Numerical results show fair differences in the temperature and humidity patterns according to the different wind incidences. Three turbulence models have been also tested. Results also show fair differences in the climatic pattern according to the mixing properties of the models. The RNG model improves the homogeneity of the climatic parameters when compared with both others models. Thus, the fine experimental determination of the velocity, temperature and humidity patterns inside the tunnel and particularly in the vicinity of the crop rows constitutes the next step for the validation of the turbulence model.

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Tables

Table 1. Characteristics of the porous media model of the tomato crop

Equation for the source term	*Values*
$S_v = -L_{ad}\rho C_d v^2$	$L_{ad} = 3\ m^{-1}$; $C_d = 0.32$

Table 2. Characteristics of the heat and water vapour balance model of the tomato crop

Variable	*Equation*
Absorbed radiation	$R(z) = R_g \exp\left(-K_c . L_{ai}(H-z)/H\right)$
Aerodynamic resistance	$r_a = 305\left(L/v\right)^{0.5}$
Stomatal resistance	$r_s = 150\left(1+\left(\exp\left(0.05\left(R(z)-49\right)\right)\right)^{-1}\right) \times$ $\left(1+0.11\exp\left(0.34\left(D_a-10\right)\right)\right)$
Heat and water vapour balance	$\frac{dR(z)}{dz} = L_{ad}\rho C_p \frac{T_l - T_a}{r_a} + L_{ad}\rho\lambda \frac{w_f - w_a}{r_a + r_s}$
Water vapour density flux	$\phi_w = L_{ad}\rho\lambda \frac{w_f - w_a}{r_a + r_s}$

Notation

C_d: drag coefficient of the crop
C_p: specific heat of air, J kg^{-1} K^{-1}
D_a: saturation deficit of air, Pa
H: height of the crop, m
k: turbulent kinetic energy, m^2 s^{-2}
K: permeability of the porous medium, m^2
L: leaf characteristic length, m
L_{ad}: leaf array density, m^{-1}
L_{ai}: leaf array index
r_a: aerodynamic resistance, s m^{-1}
r_s: stomatal resistance, s m^{-1}
R: absorbed radiation density, W m^{-2}
R_g: global radiation density inside the greenhouse, W m^{-2}
S_v: source term for the momentum equation
T_a: air temperature, K
T_f: leaf temperature, K
v: characteristic velocity of air, m s^{-1}
w_a: absolute humidity of air, kg kg^{-1}
w_l: leaf absolute humidity, kg kg^{-1}
z: vertical co-ordinate, m
ε: dissipation rate of k, m^2 s^{-3}
ϕ_w: water vapour density flux, W m^{-2}
λ: latent heat of water evaporation, J kg^{-1}
ρ : air density, kg m^{-3}

Figures

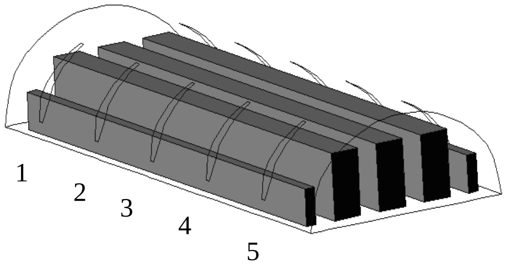

Fig. 1. Sketch of the Tunnel-type greenhouse with side-vents and tomato crop

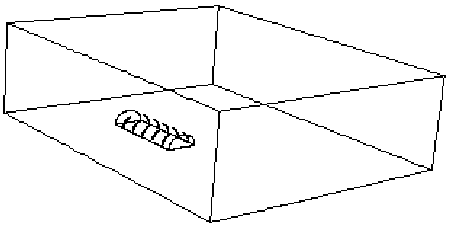

Fig.2. Sketch of the large domain model

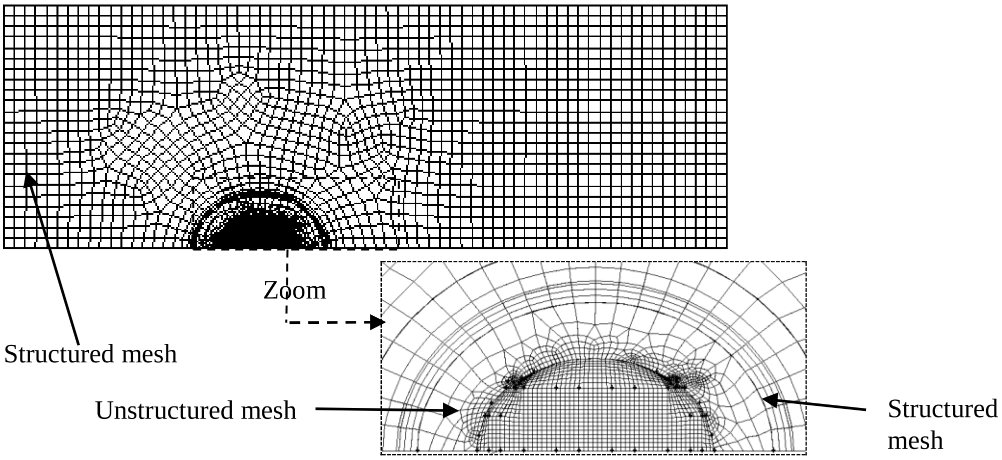

Fig.3. Sketch of the mesh for the outside and the inside (zoom) of the tunnel

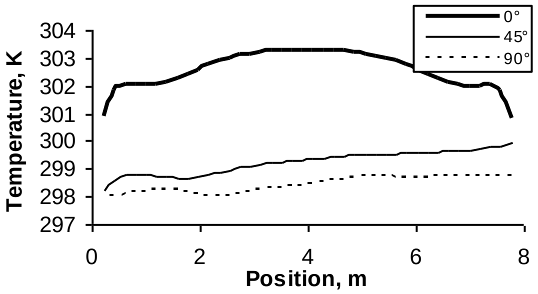

Fig.4. Temperature distribution vs. wind direction

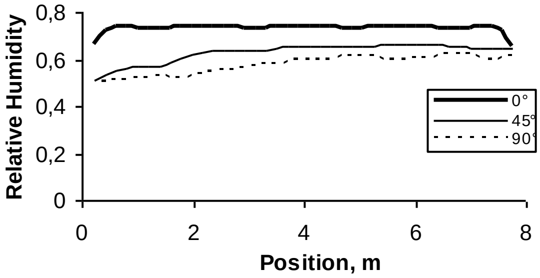

Fig.5. Humidity distribution vs. wind direction

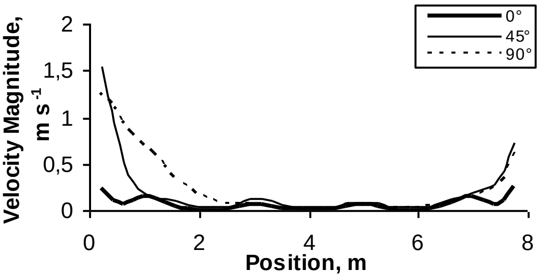

Fig.6. Velocity distribution vs. wind direction

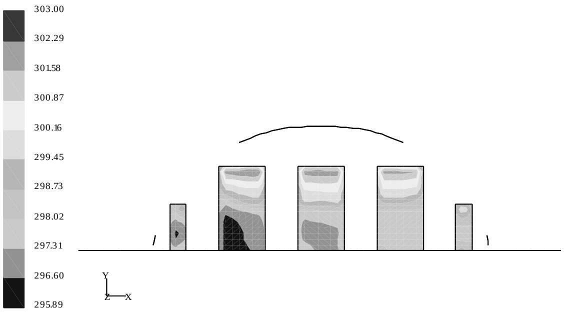

Fig.7. Temperature distribution on leaf surface in the crop rows; wind direction = 45°

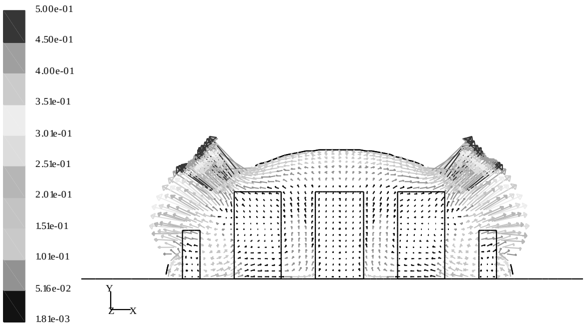

Fig.8. Velocity field in a transverse section; standard model; wind direction = 0°

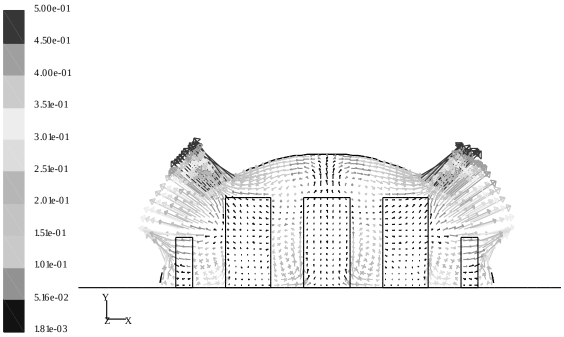

Fig.9. Velocity field in a transverse section; RNG model; wind direction = 0°

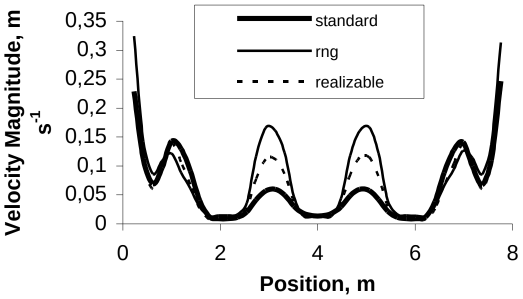

Fig.10. Velocity distribution in a transverse section as a function of the turbulence model; wind direction = 0°

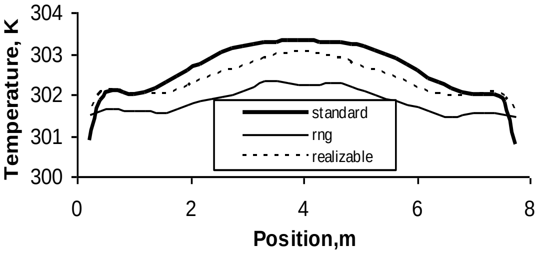

Fig.11. Velocity distribution in a transverse section as a function of the turbulence model; wind direction = 0°