Precision Modelling of Distributed Greenhouse Climate

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Abstract. A completely dynamic computational fluid dynamics model for greenhouse climate was developed and analysed. The simulations were carried out for an arc type tunnel greenhouse with a tomato crop representative of the greenhouses used in the Mediterranean region. The CFD code Fluent was used as a basis where the required external source code for the dynamic boundary conditions (written in C) was embodied. In the present paper the distribution of solar radiation during a whole day was incorporated in the crop model which is represented by the equivalent porous medium approach to model dynamic effects and a macro-model of heat and mass transfer to model the exchanges of heat and water vapour between leaves and air. Time step for the unsteady simulations was 1 sec. The results show the distribution of solar radiation and the exchanges of heat and mass between crop and air in for a whole day period and they compared with relative results from simulations carried out with steady state conditions.

Keywords: Greenhouse, indoor climate, temperature, air velocity, CFD

1 Introduction

In Controlled Environment Agricultural (CEA) systems, indoor environmental conditioning is a tool to improve the growth, development and quality of the crops and animals allowing higher yields and better quality compared with outdoor.
From many researchers in the last decade have been recognized and proved that the indoor environment in CEA systems is imperfectly mixed. Such imperfect mixing leads to gradients in variables such as temperature, humidity, gas, dust and air velocity, all of which affect the micro-environment around the animal or plant. Even in well-designed agricultural buildings, large gradients of environmental parameters exist (Bartzanas et al. 2013). The large differences, lead to higher energy and water consumption, cause non-uniform production and quality, but also lead to problems with pests and diseases. These interactions of environmental variables in production system are complex involving a number of physical and chemical properties (most of the times in different scales) of overall system and various system configurations and thus, they are not easily, if not impossible to measure it accurately, but even challenging to model them. There are several approaches and strategies for modelling and controlling the spatial heterogeneity of indoor climate of CEA systems.

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Numerical modelling techniques such as Computational Fluid Dynamics (CFD) can offer an effective way of accurately quantifying the influence of structures/machinery design, environment parameters and weather conditions within a virtual environment. Thus, the amount of physical experimentation can be reduced considerably, although, as of yet, not eliminated. CFD is a simulation method that can efficiently estimate both spatial and temporal field fluid pressure as well as other chemical and environmental scalars, and the method has proven its effectiveness in system design and optimization within the chemical, aerospace, and hydrodynamic industries (Zhang et al., 2006). Today, CFD is the art and science of analyzing and simulating systems in which a fluid flow is of central interest and in which heat and mass transfer and chemical reaction may take place. CFD became an integral part of the engineering design and analysis environment of many companies because of its ability to predict the performance of new designs or processes prior to manufacturing or implementation (Schaldach et al., 2000). The ubiquitous nature of fluids and their influence on system performance has caused a widespread take-up of CFD also in CEA (Norton et, al. 2007; Bartzanas et al., 2013). Distributed parameter modelling is now a standard operation in the application to agricultural ventilated buildings.

2 Numerical Model

The flow inside the greenhouse is assumed to be 3D, steady-state, incompressible and turbulent (Ferziger and Peric, 1996). The flow and transport phenomena for a dependant variable Φ are described by the Reynolds Averaged Navier-Stokes (RANS) equations. In momentum, equations are incorporated as source terms the natural convection effects due the temperature difference between the ground and the roof of the building and the plants' resistance. The natural convection effects are incorporated by the use of Boussinesq model, which offers faster convergence and accuracy, assuming constant density in all equations except from the calculation of buoyancy term in the momentum equations. The porous media are modelled by the addition of a momentum source term to the fluid flow equation. The specific source contribution is composed by a viscous loss term known as Darcy law and an inertial loss term.

An ideal binary mixture approach is used for the prediction of the specie distribution in order to predict the concentration of fresh air and the water vapor inside the greenhouse, for the prediction of internal humidity. In particular, the model solves for n-1 contaminants of the mixture and for the needs of the present simulation, the code is running for the water vapour concentration while the remaining quantity is corresponding to fresh air concentration. The binary diffusion coefficient based on Fick's law is a function of the local temperate and density according to Schirmer relation while the general diffusion coefficient for the species convection-diffusion equation is corrected by the addition of the mass diffusion caused by the turbulence, taking under consideration the turbulent Schmidt number.

The energy conservation is modelled by the energy transport equation taking under consideration the plants existence, modifying the thermal conductivity coefficient, and by the radiation diffusion equation. The radiation is simulated by the Discrete

Ordinates (DO) model using the approach proposed by Chui and Raithby (1993) and its contribution is adjusted properly as source term in the energy transport equation. The energy distribution inside the greenhouse and on the cover of it is calculated by a RANS type equation. Additionally, the energy equation is also solved in solid region in its reduced form, and its total calculation is derived in terms of enthalpy for better accuracy. The DO model is used for the simulation of solar incident radiation on the greenhouse cover and the internal radiation transfer. The effect of turbulence on the flow is implemented via the high Re k-ε model (Launder and Spalding 1972). The crop inside the greenhouse is simulated as a four rows of porous zone, modelling the viscous and inertial resistances of the crop according to Forchheimer equation (Miguel, 2008) while the plant's transpiration is not taken into account in the present study. The equations of mass conservation, momentum, species, turbulence, energy and radiation are resolved numerically by finite volume method, using a grid consisted of 2.9 millions of hexahedral cells and 22 blocks produced after grid independence tests. The SIMPLEC algorithm is used for pressure-velocity coupling, yielding an elliptic differential Poisson equation in order to formulate the mass conservation equation.

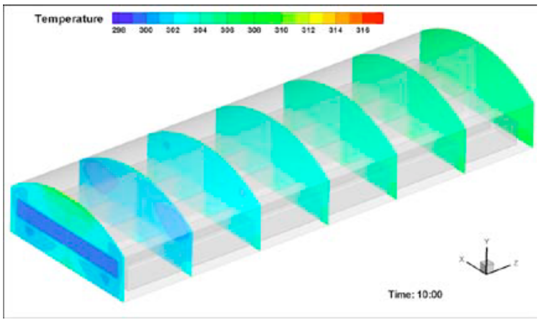
Since the major problem of the Mediterranean greenhouses is the alleviation of heat stress during the warm period of the year, the final model was tested for assessing the climate distribution in greenhouse a) under natural ventilation and b) under evaporative cooling

3 Results

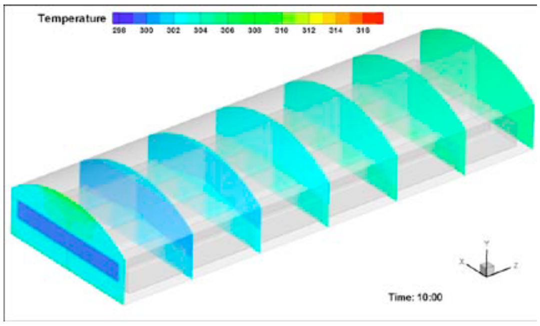
Climate distribution in a greenhouse is of major concern since it greatly influences crop growth and development. In particular, vertical temperature distribution is of great importance, since temperature has a direct effect on the sink strength at the individual plant parts. Homogeneity of solar radiation, air temperature difference and air velocity was evaluated for the two different cases studied (natural ventilation and evaporative cooling). The ratio of standard deviation of each parameter to its mean value was used as an indicator for homogeneity. Lower values of this ratio indicate more homogenous climate conditions. The use of evaporative cooling with the fans (and mainly the absence of the uncontrolled outside wind speed) leads to a more homogeneous climate conditions since little exchanges (both heat and mass) take place. Concerning the distribution of air temperature, the ratio of $\sigma(\Delta T)/\Delta T$ was 0. 43 with natural ventilation and 0.32 with the evaporative cooling. Similar patterns were observed for air humidity, solar radiation and air velocity (Table 1). Fig. 1 presents also an indicative figure of air temperature distribution (a) with natural ventilation and (b) with the use of evaporative cooling.

Table 1. Air temperature, air humidity, solar radiation and air velocity distribution inside the greenhouse.

Climate variable	Natural ventilation	Evaporative cooling
Air temperature	0.43	0.32
Air humidity	0.38	0.29
Solar radiation	0.42	0.40
Air velocity	0.52	0.25



Natural ventilation



Evaporative cooling

Fig. 1. Climate distribution inside the greenhouse.

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