Aspects of CFD modeling of fan and pad evaporative cooling system in greenhouses

A. Sapounas, C. Nikita – Martzopoulou
Aristotle University of Thessaloniki, Greece

T. Bartzanas
Technology Park of Thessaly, Greece

C. Kittas
University of Thessaly, Greece

ABSTRACT

A methodology approach in order to simulate numerically (CFD) a greenhouse equipped with fan and pad evaporative cooling system is presented. Using the main aspects of evaporative cooling systems in terms of heat and mass transfer, the flow and boundary conditions of the simulation model are identified integrating both the external and internal climatic conditions. The crop (tomato) was simulated using the equivalent porous medium approach by the addition of a momentum source term. Preliminary calculations were carried out in order the pressure drop, occurred in crop model due to air flow, to be determined as a function of leaf area and stage of crop growth. The temperature and humidity of incoming air and the operational characteristics of fans were specified to set up the CFD model. The numerical analysis was based on the Reynolds-averaged Navier-Stokes equations in conjunction with the realizable k-ε turbulence model. The finite-volume method (FVM) was used to solve the governing equations. The 3D full scale model was solved in several differencing schemes of various orders in order to examine its accuracy. The simulation approach was used mainly to identify the critical parameters of microclimate of greenhouse and the regions were these have to be measured during the upcoming experiments which will take place in Farm of Aristotle University of Thessaloniki. Results show the influence of the different airflow rates on greenhouse microclimate, indicating that the proper choice of ventilation rate is crucial factor in order to improve the efficiency of evaporative cooling systems.

1. INTRODUCTION

The current trend in greenhouse cultivation is to extend the production season, in order to maximize the use of greenhouse equipment, extend the export season, increase the annual yield per unit area and increase the profitability. Nevertheless, in many Mediterranean greenhouses such a practice is limited because the cooling method used (mainly ventilation and shading) does not provide the desired conditions, especially during the hot summer months.

Natural ventilation and roof shading are the most common techniques. Ventilation reduces greenhouse overheating, but it may even enhance the risk of water stress because it often increases crop transpiration (Seginer, 1994). Kittas et al (2001) reported that high ventilation rates were not, a priori, the best solution for alleviating crop stress in greenhouses during summer conditions. Shading screens mounted externally or internally, may be used to reduce radiation inside the greenhouse but the effective temperature reduction is not really proportional to the shading rate. Willits and Peet (1993) showed that externally mounted black polyethylene films were less than 50% effective in reducing energy and temperature gains compared to their commercially given values, while white shading cloths were only slightly more effective.

If the greenhouse air temperature has to be kept near or below outside ambient temperatures, some form of cooling must be provided. Evaporative systems for cooling greenhouses have been developed to provide the desired growing conditions in the greenhouse during the hot period of the year. The principle underlying direct evaporative cooling is the easy conversion of sensible to latent heat (unsaturated air is cooled by exposure to free and colder water, both thermal isolated from other influences. Some of the air’s sensible heat transfers to the water and becomes latent heat by evaporative some of the water while the latent heat follows the water vapour and diffuses to the air. Direct evaporative cooling can be done by spraying water droplets in a naturally ventilated greenhouse (by low or high pressure fog systems), or by forcing ambient air through wet pads. Both produce a temperature drop with an absolute humidity rise in the greenhouse, which contributes to
decrease the vapour pressure deficit and moderate the transpiration demand (Katsoulas et al., 2001). Various works on evaporative cooling systems applied to horticulture, mainly fog systems, were already published, and, among others, those by Montero et al. (1981, 1990) and Giacomelli et al., (1985). Most of these works analyse the thermodynamic efficiency of the system and its climatic effects. Segner (1994) found that evaporative cooling systems are mainly effective when crop transpiration is low, and Fuchs (1993) reported that a highly transpiring crop combined with a proper ventilation rate is the most effective mechanism to keep leaf temperatures moderate. A theoretical study was conducted by Arbel et al. (1999) to evaluate an evaporative cooling system for greenhouses by installing uniformly distributed fog generating nozzles in the space over the plants. Landsberg et al., (1979), proposed a theoretical model for the efficiency of evaporative cooling in different physical conditions and Bowen ratios. One limitation of this model is the a priori specification of the sensible heat to latent heat ratio rather than its deduction from actual crop behaviour. Moreover, this model was not tested against experimental data. More recently, Willits (2000) proposed a model to predict air and crop temperatures as a function of ventilation rate and external temperature and Kittas et al. (2003) present and validate a model to predict temperature gradients in a large evaporative cooled greenhouse. The advantages of this method lie in its simplicity of operation and control and also in that it does not entail any risk of wetting the foliage. The main disadvantages are high cost and lack of uniformity of the climatic conditions which expressed with large temperature and humidity gradients along the greenhouse (from evaporative pads to extracting fans). The amplitude of such gradients is affected by many factors such as the geometry of the greenhouse, the outside climate conditions, the ventilation rate of the extracting fans and the flow rate of the water in the evaporative pads. In order to determine the influence of each parameter experimental investigations could be carried out, but these would be very expensive in time and money. Moreover it is very difficult to give fairly identical and stable boundary conditions in a field experiment, due to unstable and unpredictable weather conditions. Dynamic (Landsberg et al., 1979) or analytical models (Kittas et al., 2003, Willits 2003) can be used alternatively for this purpose. Recent progress in flow modelling using computational fluid dynamics is also a good alternative. Computational fluids dynamics is an advanced method for design in engineering; it is increasingly being used to analyze greenhouse microclimate with respect to structural specifications (Boulard and Wang, 2002; Bartzanas et al., 2004). Aim of the present study was is to develop a methodology approach in order to simulate numerically (CFD) a greenhouse equipped with fan and pad evaporative cooling system in order to identify the critical parameters that affect the efficiency of fan and pad evaporative cooling systems in greenhouses. The next step will be the experimental verification of the proposed numerical model and the comparison of the numerical results with the results obtained by previous developed and experimentally tested analytical model (Kittas et al., 2003) which considered the greenhouse as a heat exchanger. The finite-volume method (FVM) was used to solve the governing equations on the computational grid of a 3D full scale model. In computation, several differencing schemes of various orders are outlined and their accuracy is examined.

2. MATERIALS AND METHODS

The CFD technique numerically solved the Navier-Stokes equations and the mass and energy conservation equations. The three dimensional conservation equations describing the transport phenomena for steady flows in free convection are of the general form:

$$\frac{\partial (U \Phi)}{\partial x} + \frac{\partial (V \Phi)}{\partial y} + \frac{\partial (W \Phi)}{\partial z} = \nabla \cdot \Phi + S_0$$

In Eqn (1), $\Phi$ represents the concentration of the transported quantity in a dimensionless form, namely the three momentum conservation equations (the Navier-Stokes equations) and the scalars mass and energy conservation equations; $U, V$ and $W$ are the components of velocity vector; $\Gamma$ is the diffusion coefficient; and $S_0$ is the source term. The governing equations are discretized following the procedure described by Patankar (1980). This consists of integrating the governing equations over a control volume.

The commercially available CFD code Fluent® (1998) was used for this study. Fluent® code uses a finite volume numerical scheme to solve the equations of conservation for the different transported quantities in the flow (mass, momentum, energy, water vapour concentration). The code first performs the coupled resolution of the pressure and velocity fields and then the others parameters, like temperature or water vapour concentration. Special items like the mechanical or climatic behaviour of the rows of tomato crop are determined using a customization, i.e a routine included in a used defined file (UDF) and built for the determination of the parameters exclusively relevant to the vegetation. The domain of interest was generated and then meshed using the integrated pre-processor of Fluent, Gambit.

The grid structure was an unstructured, quadrilateral mesh with a higher density in critical portions of the flow subject to strong gradients. The mesh consists of 53920...
cells for the half of the greenhouse, as a geometrical symmetry of the model allows solving the model symmetrically. After several tries with different densities, the calculations were based on a 15 m (in x direction) by 8 m (in y direction) by 4.17 m (in z direction, ridge height of greenhouse) grid (Fig. 1). This results from an empirical compromise between a dense grid, associated with a long computational time, and a less dense one, associated with a marked deterioration of the simulated results. Moreover the grid quality was checked using as a criterion the EquiAngleSkew criterion (Fluent, 1998) and it was characterised as very good.

Wall type boundary conditions was imposed along the floor (39 °C), the roof (35 °C) and the side walls (35 °C). The classical no-slip boundary conditions are assumed for the walls. The standard k-ε model (Launder and Spalding, 1974) assuming isotropic turbulence was adopted in this study to describe turbulent transport. The species model was activated to account the transport of air vapour inside the greenhouse. The crop was simulated using the equivalent porous medium approach (Boulard and Wang, 2002) by the addition of a momentum source term, due to the drag effect of the crop, to the standard fluid flow equations.

The simulation model was solved for three different ventilation rates corresponds to the air flow through the fans. The ventilation rates in terms of m$^3$ m$^{-2}$ s$^{-1}$ for the three tested cases were, 0.0245 (case 1), 0.0184 (case 2) and 0.0123 (case 3). For all the cases the external dry bulb temperature was 35 °C, the internal dry bulb temperature of the incoming air exactly after the pad was 27 °C, with mass fraction of water vapour of 0.0132 which leads to 59.80% air relative humidity. The imposed boundary conditions are the average daily values from measurements in the experimental greenhouse in a typical hot summer day.

3. RESULTS

Numerical results show that the tested cooling system was able to keep the greenhouse temperature several degrees below outside air temperature for the three tested air flow rates of extracting fans. The highest the airflow rate the lower the air temperature increase the greenhouse. Mean air temperature inside the greenhouse was 30.5 °C for the lowest air flow rate and it was reduced to 29.6 °C and to 28.8 °C for the other two airflow rates. Although the length of the greenhouse it is no too long, important thermal gradients were observed in the direction for evaporative pads to extracting fans. Figure 1 shows the air temperatures along greenhouse length at the middle of the greenhouse for the three tested airflow rates: a gradual temperature rise, from the pads to the fans, reaches almost 6 °C when the lower airflow rate was used. A thermal gradient was also observed in the vertical direction, from greenhouse ground to greenhouse roof. However, the largest ventilation rates are not always the best solution to cool the greenhouse. The air velocity near the crop and the temperature difference must also be taken into account since there are important factors influencing the uniform growth of crop.

Spatial heterogeneity of air velocity and climate inside greenhouse interfere with plants activity and influence largely crop behaviour through their effects on crop gas exchanges, particularly transpiration and photosynthesis. For instance increasing air velocity inside the greenhouse increases convective heat transfers and hence reduces the leaf – air temperature difference. Furthermore, air velocity might be expected to increase photosynthesis because of the reduced boundary layer resistance to the transport of carbon dioxide. Air velocity just after the evaporative pads was 0.8 m s$^{-1}$ when the highest airflow rate was used and it was reduced to 0.6 and to 0.4 for m s$^{-1}$ the other two airflow rates. Mean air velocity in the middle of the crop level was 0.52 with the highest ventilation rate and it was reduced to 0.35 and 0.18 with the other two used ventilation rates. Figure 3 presents the computed contours of air velocity when the highest ventilation rate was used.

Figure 1. Air temperature distribution along greenhouse length at the middle of the greenhouse — (case 1), - - - - - - (case 2) and ■ ■ ■ (case 3).

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Figure 2. Computed contours of air velocity when the highest ventilation rate was used.
4. CONCLUSIONS

A methodology approach in order to simulate numerically a greenhouse equipped with fan and pad evaporative cooling system was presented in this paper. The influence of three different airflow rates of the extracting fans on air temperature and air velocity distribution inside the greenhouse was presented to demonstrate the capabilities of the numerical code to be used as a design tool in order to improve the efficiency of fan and pad evaporative cooling systems in greenhouses. Increasing the ventilation rate beyond a certain value in this greenhouse does not necessarily produce an overall better growing environment for the plants.

The numerical model is proved to be a useful tool in order to study the performance of cooling pad systems for rational greenhouse design. Furthermore, greater emphasis should be placed on the uniformity of conditions within the crop canopy rather than on the differences between the pad inlet and fan exhaust locations.

REFERENCES


