Numerical and Experimental Study of Fan and Pad Evaporative Cooling System in a Greenhouse with Tomato Crop

A.A. Sapounas, Ch. Nikita-Martzopoulou and G. Martzopoulos
Department of Hydraulics
Soil Science and Agriculture Engineering
School of Agriculture
Aristotle University of Thessaloniki
54124 (229) Thessaloniki
Greece

Keywords: CFD, temperature, humidity, air-flow

Abstract

An experimental greenhouse equipped with fan and pad evaporative cooling is simulated numerically using a commercial CFD code. The main aspects of evaporative cooling systems, in terms of heat and mass transfer and both the external and internal climatic conditions were integrated to set up the numerical model. The crop (tomato) was simulated using the equivalent porous medium approach by the addition of a momentum and energy source term. Preliminary calculations were carried out and validated by experimental measurements, in order the pressure drop occurred in crop model due to air flow, to be determined as a function of leaf area, stage of crop growth and cultivation technique. The temperature and humidity of incoming air and the operational characteristics of exhaust 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 RNG 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 results were validated with experimental measurements obtained at a height level of 1.2 m above the ground in the middle of the crop canopy at 23 and 8 points, concerning air temperature and air humidity respectively. The correlation coefficient between computational results and experimental data was at the order of 0.7419 for air temperature and 0.8082 for air relative humidity. The results showing that the evaporative cooling system for greenhouses could be effectively parameterized in numerical terms, providing a useful tool in order to improve system’s efficiency.

INTRODUCTION

One of the most important issue in modern 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.

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 while unsaturated air is cooled by exposure to free and colder water, both thermal
isolated from other influences. 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. Seginer (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. More recently, Willits (2003) proposed a numerical model to predict air and crop temperatures as a function of ventilation rate and external temperature; Kittas et al. (2003) present and validate a model to predict temperature gradients in a large evaporative cooled greenhouse and finally Fuchs et al. (2006) developed and validated a numerical model based on energy balance equation which solved numerically.

The main advantage of fan and pad evaporative cooling system lies in its simplicity of operation and control and also in that it does not entail any risk of wetting the foliage. The main drawback is 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 exhaust 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 and the flow rate of the water in the evaporative pad. 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 or numerical (Landsberg et al., 1979) or analytical models (Kittas et al., 2003, Willits, 2003, Fuchs et al., 2006) can be used alternative for this purpose. Recent progress in flow modelling using computational fluid dynamics is also a good alternative. Computational fluids dynamics is an advanced technique 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).

Even the temperature gradients from pad to fans are well described by many researchers, we have pure knowledge about how the air flow, resulted by the negative pressure of a combined operation of different fans, affect the cooling efficiency, especially in large greenhouses and how the variable speed fans could be integrated to modern environmental control systems. Aim of the present study is to simulate numerically (CFD) an experimental greenhouse equipped with fan and pad evaporative cooling system. The commercial CFD code Fluent® was used to set up the numerical model. Finally the computational results compared with experimental data obtained during experiments conducted the summer period of 2006 in Farm of Aristotle University of Thessaloniki.

MATERIALS AND METHODS

The experiments were carried out in a single-span, 8m x 15m greenhouse with an arched roof (Fig. 1); it’s orientation was 30º from North and its position was at: Latitude 40.54 N, Longitude: 22.99 E. The greenhouse had FRP (fiberglass reinforced plastic) sidewalls and a tetrafluoroethylene copolymer 60 microns film roof. The gutter height was 2.6 m and the ridge height was 4.2 m. A cooling pad of width 6.0 m and height 1.0 m was positioned at the center of the north-wall, at 1.0 m above the ground. On the south wall, two fans, with propeller diameter of 0.76 m and 0.60 respectively, were placed at
1.32 m above the ground.

The period of measurement, from August to September 2006, coincided with the nature stage of tomato crop cultivated using the common one stem technique (162 plants were transplanted at 3 June 2006). During experiments the following measurements were recorded by a data logger system. Outside the greenhouse: air temperature, air humidity, air speed and direction at 10.0 m height from the ground, global and diffuse radiation. Inside the greenhouse (Fig. 1): air temperature at 23 points 1.2 m above the ground (thermistors & Hobo Pro data loggers); air humidity at 8 points in the same horizontal level (Hobo Pro data loggers); solar radiation above the canopy (pyranometer with thermopile sensor); leaf wetness (Hobo Leaf Wetness Smart Sensor); soil moisture content (Hobo Pro microstation) and leaf temperature (thermistors constantly and an infrared sensor periodically). While the evaporative cooling system was operating, measurements were obtained with 2D Sonic anemometer at inside the greenhouse (19 points), at foreside of pad (15 points) and outside of fans (9 points). Every week the leaf area index was recorded at 30 locations with a Sun Scan canopy analysis system (Delta-T Devices Ltd). Pad water rate was measured by an integrated flow meter which was connected to the makeup water line to the pad storage tank and the operation time of the pump was recorder with an electrical on/off sensor.

The experimental greenhouse was designed and meshed with the geometrical processor Gambit® as a 3D full scale model. The main characteristics of the experimental greenhouse, such as pad, fans, frame, covering materials and individual plants, were thoroughly integrated in the geometrical model (Fig. 1). 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 1017652 cells, result provided after many attempts in order to achieve grid independent results and acceptable time needed for the convergence. Moreover the grid quality was checked using as a criterion the EquiAngleSkew criterion (Fluent, 1998) and it was characterised as very good for the 92% of the cells.

The commercially available CFD code Fluent® (1998) uses a finite volume numerical scheme to solve the equations of conservation for the different transported quantities in the flow (mass, momentum, energy and water vapour concentration). The set up of simulation model mainly consisted of the definition of boundary conditions which based on experimental data obtained the specific time period. The RNG k-ε model (Launder and Spalding, 1974) assuming isotropic turbulence was adopted to describe turbulent transport. The species model was activated to simulate the transport of air vapour inside the greenhouse due to the air flow through the pad and crop transpiration. The incoming air consisted of air and water vapour in a mass fraction corresponds to the relative humidity recorder by the humidity sensors. The crop was simulated using the equivalent porous medium approach (Boulard and Wang, 2002; Lee and Short, 2001), as a source term of both latent and sensible heat and as a sink momentum which dominated by viscous and inertial resistance factors. The influence of greenhouse’s surrounding area concerning the heat transfer coefficient from the covering materials were specified through experiments and preliminary CFD calculations of a large realistic domain. The main definitions of simulation model are presented in Table 1. The calculations were carried out according to the following variables; leaf area index (2.5), leaf wetness (72%), canopy temperature (28°C), outside temperature (34.9°C), characteristic leaf dimension (0.1), inside solar radiation above the canopy (610 W m⁻²), crop volume (87.54 m⁻³) and atmospheric pressure (101.3 kPa). The air density and the latent heat of vaporization of water were calculated according to the equations described by Fuchs et al. (2006).

RESULTS AND DISCUSSION

The simulation model based on the experimental data obtained at 5/9/2006 14:00 (recording interval 1 min, average values of a period 15 minutes). The numerical results showed that the tested cooling system was able to keep the greenhouse temperature only few degrees below outside air temperature for the specific ventilation rate. Although the
length of the greenhouse it is not too long, important thermal gradients were observed in the direction from evaporative pads to exhaust fans. Figure 2 shows the air temperatures along greenhouse length at a cross section surface 1.2 m above the ground. A thermal gradient was also observed in the vertical direction, from greenhouse ground to greenhouse roof. The average air temperature at the greenhouse was 31.45°C while during the experiments the average temperature recorded by 23 sensors was 32.06. Even if these values are quite close, the simulation results varied in a range of -8% - 5% (Fig. 3). During experiments the highest temperatures were recorded inside the crop canopy, and the lowest beneath of it. The simulation model underestimates the air temperature inside the crop canopy and overestimates the air temperature near the fans. This is mainly due to the fact that during the experiments part of the cold air, entering the greenhouse from wet pad, passed below the canopy with velocities at the order of 0.3-0.4 m/s (Fig. 4), while at the same time the air velocities inside the crop canopy ranged from 0.05-0.1 m/s (Fig. 4). The same phenomenon appeared during the experimental process. Indeed the air passed below the canopy as the tomato crop was cultivated according to the one stem technique. When the measurements were obtained the main stem of each plant was without leafs till 0.5 m above the ground resulting obviously a reduction of the crop resistance to the air flow.

A good agreement between simulation results and experimental data was found for the air relatively humidity too. The average air relative humidity at the greenhouse was 58.33% while during the experiments the average values recorded by 8 sensors were 54.72%. The simulation results varied in a range of 0.3% - 15.9%. (Fig. 5), although these conclusions are not strong enough, as two of the humidity sensors were located just in front of the wet pad.

The simulation results showed not only the key role of the ventilation rate, but also how the specific characteristics of the air flow inside the greenhouse influences the performance of the fan and pad evaporative cooling system. The cooling efficiency, which expressed as a function of outside air temperature and inside wet bulb temperature entering the greenhouse, can not provide detailed information about the heat removal due to system’s operation.

In this study a numerical model based on experimental data was presented to demonstrate the capabilities of the numerical code 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 does not necessarily produce an overall better growing environment for the plants as the air flow characteristics dominated the phenomenon. 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.

**Literature Cited**


**Tables**

Table 1. Main constant input values used in 3D CFD model.

<table>
<thead>
<tr>
<th>Boundary element</th>
<th>Type</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature of FRP</td>
<td>Wall</td>
<td>38</td>
<td>ºC</td>
</tr>
<tr>
<td>Temperature of Alfex</td>
<td>Wall</td>
<td>40</td>
<td>ºC</td>
</tr>
<tr>
<td>Temperature of frame - sides</td>
<td>Wall</td>
<td>42</td>
<td>ºC</td>
</tr>
<tr>
<td>Temperature of frame - roof</td>
<td>Wall</td>
<td>45</td>
<td>ºC</td>
</tr>
<tr>
<td>Temperature of greenhouse ground</td>
<td>Wall</td>
<td>34</td>
<td>ºC</td>
</tr>
<tr>
<td>Air velocity of pad</td>
<td>Velocity Inlet</td>
<td>0.754</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>Air temperature of pad</td>
<td>Velocity Inlet</td>
<td>27.39</td>
<td>ºC</td>
</tr>
<tr>
<td>Pressure of fan-1</td>
<td>Exhaust fan</td>
<td>-30.0</td>
<td>Pa</td>
</tr>
<tr>
<td>Pressure of fan-2</td>
<td>Exhaust fan</td>
<td>-38.0</td>
<td>Pa</td>
</tr>
<tr>
<td>Turbulent kinetic energy</td>
<td>5.0</td>
<td>m² s⁻²</td>
<td></td>
</tr>
<tr>
<td>Turbulent dissipation rate</td>
<td>2.0</td>
<td>m² s⁻³</td>
<td></td>
</tr>
<tr>
<td>Mass fraction of water vapor</td>
<td>0.014316</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensible heat of plants</td>
<td>0.000316</td>
<td>kg m⁻³ s⁻¹</td>
<td></td>
</tr>
<tr>
<td>Latent heat of plants</td>
<td>97.36</td>
<td>W m⁻³</td>
<td></td>
</tr>
<tr>
<td>Viscous resistance</td>
<td>2.532</td>
<td>m⁻¹</td>
<td></td>
</tr>
<tr>
<td>Inertial resistance</td>
<td>1.92</td>
<td>m⁻¹</td>
<td></td>
</tr>
<tr>
<td>Porosity of the plant canopy</td>
<td>20</td>
<td>%</td>
<td></td>
</tr>
</tbody>
</table>
Figures

Fig. 1. (a) Wire-frame rendering of the greenhouse CAD model designed by Gambit® and experimental measurement points Θ at level 1.2 m above ground. (b) 3D full scale simulation model of the experimental greenhouse with individual tomato plants.

Fig. 2. Contours of air temperature in a plane surface 1.2 m above the ground (range 26 – 34 °C).
Fig. 3. Comparison of simulation results and experimental data. (a) XY scattering of air temperature inside the greenhouse from pad to fans and (b) distribution at the different sensors points (where: $T =$ temperature and $TH =$ temperature & humidity).

Fig. 4. Contours of air velocity in a transverse section in the middle of the greenhouse; range 0-0.5 m/s.
Fig. 5. Comparison of simulation results and experimental data. (a) XY scattering of air relative humidity inside the greenhouse from pad to fans and (b) distribution at the different sensors points (where TH = temperature & humidity).