Influence of vents type arrangement on greenhouse thermal driven ventilation

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ABSTRACT

A numerical analysis of the natural ventilation in greenhouses was performed at no-wind and low-wind speeds with the use of Computational Fluid Dynamics (CFD). Imposed boundary conditions correspond to the average measured experimental values during a ten day's period. Numerical predictions of the ventilation efficiency and microclimate distribution of an arch type tunnel greenhouse, a typical Mediterranean-type greenhouse were obtained for various ventilator configurations. Quantitative and qualitative results concerning airflow and air temperature distribution for four different vents configurations were collected and analysed. Numerical predictions of natural ventilation agreed well with relative published data. Results show the importance of combining roof and sidewall ventilators for efficient thermally driven ventilation.

1.INTRODUCTION

Excessive temperature is probably the most serious problem faced by greenhouse growers in hot and warm Countries like the Mediterranean area. In fact due to the high thermal loads during the warm period, growers are forced to reduce cultivation period. Attempts have been made to reduce the greenhouse temperature by shading greenhouses (Baille et al. 2001) or evaporative cooling (Kittas et al. 2003). However the majority of greenhouses in the Mediterranean area are rudimentary equipment and natural ventilation is the primary control tool to manage greenhouse microclimate. Natural ventilation driving force is the combination of buoyancy and wind effects, and their relative importance depends on the wind speed and the internal to external temperature differential. In these greenhouses, ventilation plays a key role in determining the greenhouse microclimate, affecting specifically the temperature, humidity and composition of the greenhouse air, and influencing crop growth and development.

The most unfavourable conditions for ventilation are when the wind speed is near zero and thermal effects control the exchange of air. This is particularly crucial during calm summer periods when greenhouse cooling is needed. Until recently, most studies of natural ventilation were based on estimates of a global air exchange rate from tracer gas measurements (Boulard and Baille, 1995) or energy balance methods (Kimball, 1986), which provides no details of internal flow patterns and temperature profiles. These studies assumed a global homogeneity of the greenhouse atmosphere and a uniform air temperature and a uniform air velocity are applied. However, this is not the case, since greenhouse microclimate was characterized by strong heterogeneity. Recent progress in computer performance and developments in flow modelling using computational fluid dynamics (CFD) provide a new opportunity to analyse the heterogeneity of greenhouse microclimate. In the CFD model actual weather conditions and structural specifications can be change easily while maintaining stable boundary conditions. Since the pioneering works of Nara (1979) in assessing the distributed climate in a greenhouse, many studies have been undertaken to achieve a better understanding of the ventilation mechanism in greenhouses, even in vary large structures (Fatnassi et al. 2003; Campen and Bot, 2003; Bartzanas et al. 2004). In many regions with intense greenhouse cultivation, weak wind situations coincide with high temperatures, when high ventilation efficiency is mostly required. Therefore, the investigation of the structural characteristics of greenhouses influencing the ventilation process at low-wind-speeds can offer hints for improvements of the greenhouse design towards more efficient thermally driven ventilation. Aim of the present study was to numerically investigate the influence of four commonly found vent configuration on airflow and temperature patterns in a typical Mediterranean greenhouse type at zero and low wind speeds

2. NUMERICAL MODEL

2.1 Model description

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 form:

$$\frac{\partial(U\Phi)}{\partial x}+\frac{\partial(V\Phi)}{\partial y}+\frac{\partial(W\Phi)}{\partial z}=\Gamma\nabla^2\Phi+S_\Phi \quad (1)$$

In Eqn (1), Φ represents the concentration of the transport 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; Γ is the diffusion coefficient; and S_Φ is the source term. The governing equations are discretised following the procedure described by Patankar (1980). This consists of integrating the governing equations over a control volume. The commercially available CFD code CFX® was used for this study. CFX® code uses a finite volume numerical scheme to solve the equations of conservation for the different transported quantities in the flow. 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 behavior 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.

For the simulations a 3-D model was developed. For the geometry, a control volume was selected representing a large domain including the greenhouse. The tested greenhouse was an arch type tunnel greenhouse, which geometrical characteristics were as follows: eaves height of 2.4 m; ridge height of 4.1 m; total width of 8 m; and total length of 20 m (Fig. 1). The grid structure was an unstructured, quadrilateral mesh with a higher density in critical portions of the flow subject to strong gradients (Fig. 1). The final grid size was the result of 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.

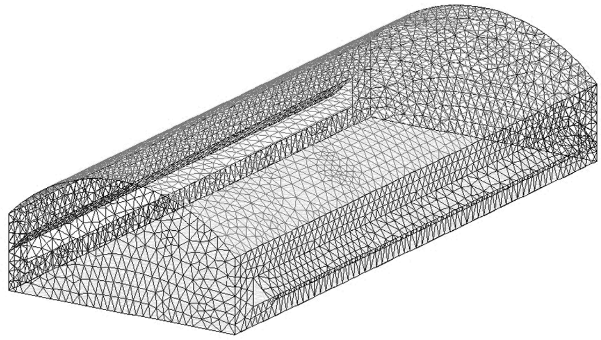

Figure 1. Detailed grid description of the tested greenhouse

The standard k-ε model (Launder and Spalding, 1974) assuming isotropic turbulence was adopted in this study to describe turbulent transport. This choice is a good compromise for a realistic description of turbulence and computational efficiency. The standard k-ε model is a semi-empirical model based on model transport equations for the turbulent kinetic energy (k) and its dissipation rate (ε) The wind direction was perpendicular to the ridge. At the inlet of the computational domain a logarithmic inlet velocity profile (atmospheric boundary layer model) was considered. Wall –type boundary conditions was imposed along the floor, the roof and the side walls. The boundary conditions were selected from average values of experimental data (Table 1). The classical no-slip boundary conditions are assumed for the walls. 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.

Table 1. Boundary conditions used in the simulations

Parameter	Value
Wind speed	0, 0.5 and 1 ms^{-1}
Wind direction	Perpendicular to greenhouse axis
Air temperature	28 °C
Roof temperature	32 °C
Greenhouse ground temperature	45 °C
Soil temperature	30 °C
Solar radiation	950 Wm^{-2}

The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm was applied to solve the flow field.

2.1 Vent configurations used for simulation

The following commonly found vent configurations have been used for the simulation of the influence of the vent design on thermally driven ventilation of a tunnel type greenhouse (Fig. 1).

2.1.1 Configuration (a): side openings only (roll-up type)

The greenhouse is equipped with two continuous rollup type openings located at 0.6 m above ground with an opening height of 0.9 m.

2.1.2 Configuration (b): side only openings (pivoting door type)

The greenhouse is equipped with two continuous pivoting door type side openings. The base of the window is at 0.6 m above ground, the height of the window is 0.9 m and the aperture angle is 45°.

2.1.3 Configuration (c): roof opening only

The greenhouse is equipped with a pivoting type roof opening. The free end of the opening is at the ridge of the greenhouse and the articulation at 0.9 m leeward from the ridge. When opened, the opening faces the wind and its chord is 0.9 m.

2.1.4 Configuration (d): combined roof and side openings (roll-up type)

This configuration combines the roll-up side openings of configuration (a) with the roof opening of configuration (c).

3. RESULTS

Figure 2 presents the computed velocity vectors for the greenhouse equipped with side only openings (configuration b) when the ventilation is purely thermal driven (i.e the outside wind speed was 0 m/s).

Two circulating cells were observed in the cross-section, each occupying nearly half the cross-sectional area. The first one, on the left-hand side, was anti-clockwise, and the second one on the other side was clockwise. Both cells met in the central vertical axis of the greenhouse. So, due to the strong mixing, a more or less uniform temperature in the growing area was achieved.

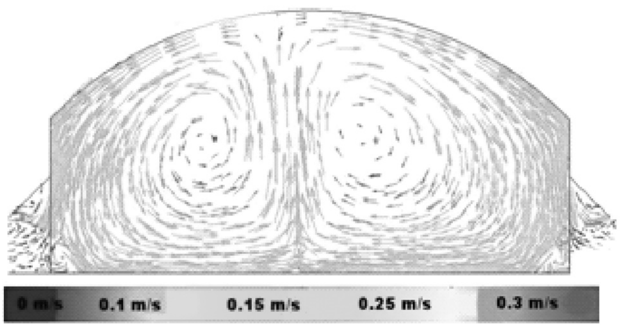

Figure 2. Computed velocity vectors for an outside wind speed of 0 m/s (configuration b)

The flow of the warm air is almost vertical due to the buoyancy effect and it reaches greenhouse rood before it exits through the side openings. Similar airflow and temperature patterns were observed by Lamrani et al (2001) using a small scale greenhouse in a wind tunnel.

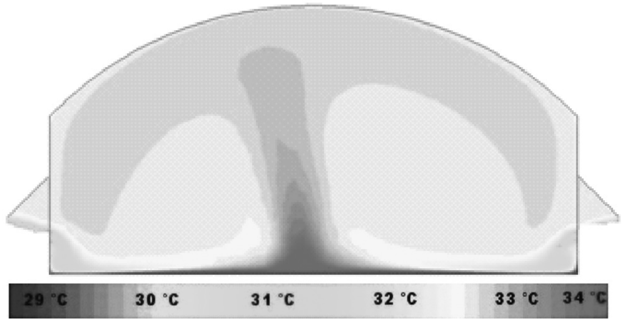

Figure 3. Computed temperature contours for an outside wind speed of 0 m/s (configuration b)

For the first vent configuration similar with the first vent configuration airflow and temperature pattern was observed. The airflow was thermally driven and the different vent configuration cannot alter the distribution of climate variables within the greenhouse.

With roof only openings (configuration c) the unique ventilation opening act simultaneously as inlet and outlet of air. For the case of roof and sides opening (configuration d) results shown a strong current of cool air entering the greenhouse through the side openings, while the internal hotter air is pushed outwards through the roof opening (Fig. 4).

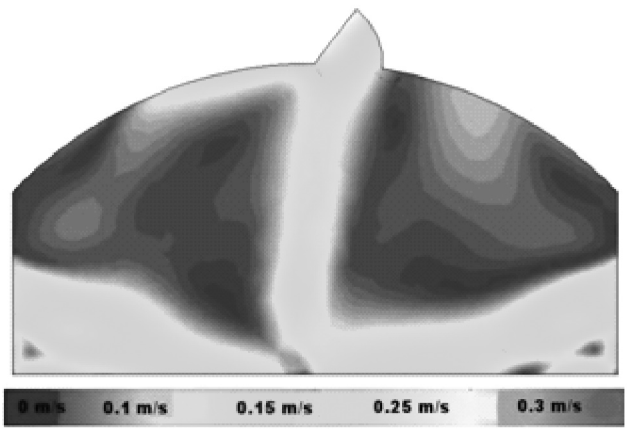

Figure 4. Computed contours of velocity for an outside wind speed of 0 m/s (configuration d)

It is clear that the role of roof openings is particularly important in stimulating an efficient air exchange, when only the buoyancy effect is considered. In this case, the side openings are the main inlet of the cool outside air, while the roof ventilators are acted as outlets of hotter air (Fig. 5).

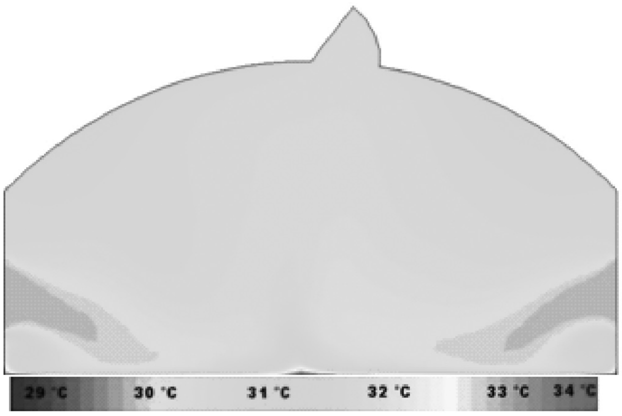

Figure 5. Computed temperature contours for an outside wind speed of 0 m/s (configuration d)

At low wind speeds (0.5 m/s), the buoyancy effect is still the main driving force of the ventilation flow. As a result airflow and temperature patterns appears qualitatively, similar to the one corresponding to the zero-wind speed. Qualitatively the airflow pattern is similar for the tested vent configurations, except from the configuration with roof only openings. Quantitative high air velocities prevails with the combination of roof and side openings, air velocities are similar for the two configurations with side only openings (configurations a and b) whereas lower air velocities occurs with roof only openings (Fig. 6).

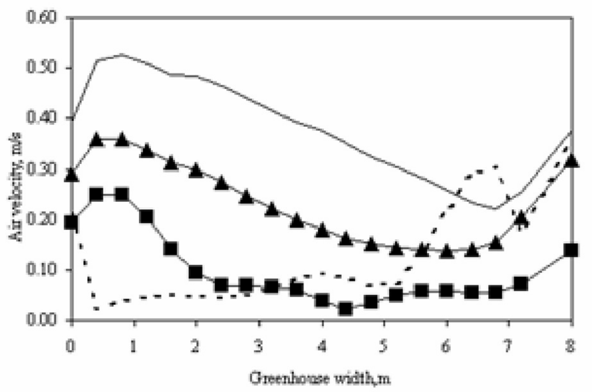

Figure 6. Air velocity distribution along greenhouse width at a height of 1 m from greenhouse ground for the four different vent configurations for an outside wind speed of 0.5 m/s, (—▲— configuration a, —■— configuration b, (- - - - configuration c, —— configuration d)

When the outside wind speed increased to 1 m/s then greenhouse ventilation is both thermally and wind driven. With side only openings (configuration a) airflow was characterized by a strong air current near the ground and a re-circulation loop with slower speed situated near the roof and flowing counter current with respect to outside wind. In the region covered by the crop the air temperature is similar to the outside due to the strong air stream in this region. The mean air temperature difference at his zone and the outside air was 0.5 °C.

With the second vent configuration airflow pattern shows that the incoming air through the windward side ventilator tends to move up immediately by the influence of inclined ventilator flap and mainly follows the inner surface of the roof. In the space to be occupied with a crop, the reverse flow due to secondary circulation result in the significant decrease of the air velocity. In the region covered by the crop the air temperature was higher than the outside since the main air steam was guided to the roof of the greenhouse. As a result, mean air temperature difference at his zone and the outside air was 2.1 °C.

With roof only openings (configuration c) the incoming air from the roof opening guided by the greenhouse walls it follows a semi – spiral trajectory and leaves the greenhouse by following the internal surface of the walls and the roof. However, still air conditions prevail at the center of the greenhouse. In the region covered by the crop mean air temperature difference at his zone and the outside air was 2.5 °C. Similar results were obtained experimentally by Montero et al (2002).

With the combination of roof and side openings (configuration d) airflow was qualitatively similar with configuration (a) because little exchange was observed through the roof opening as the external flow passed directly through the side openings. In the region covered by the crop the air temperature is similar to the outside.

4. DISCUSSION

The ventilation of a greenhouse is the exchange of air between the inside and outside atmosphere in order to dissipate the surplus heat to enhance the exchange of carbon dioxide and oxygen and to maintain acceptable humidity levels. A well designed greenhouse with a high air renewal rate uniformly reduces the indoor temperature by ventilation, especially at the canopy level. In table 2 the average values of air temperature difference between inside and outside air and of the mean air velocity for the four different vent configurations were presented for the three tested wind speeds.

From the four tested configurations, configuration d (combined roof and sides openings) achieves the highest ventilation rate, and configuration c (roof opening only) the lowest. Mean air velocity with configuration d was 0.43 m/s for an outside wind speed of 1 m/s and it was reduced to 0.14 m/s for the same wind speed when the ventilation was performed through roof only openings. For zero wind speed, mean air temperature difference between inside and outside air was 2.4 °C, it was reduced to 1.7 °C for a wind speed of 0.5 m/s and it further reduced to 0.65 °C for a wind speed of 1 m/s.

For the last outside wind speed the corresponding mean temperature difference for the other three different vent configuration were 0.84 °C (configuration a), 1.63 °C (configuration b) and 2.3 °C (configuration c)

Table 2. Average values of air temperature difference between inside and outside air and mean air velocity for the four different vent configurations for the three tested wind speeds.

Case	Mean air temperature difference between inside and outside air, °C		
	0m/s	0.5m/s	1m/s
a	4.93	2	0.84
b	3.85	2.15	1.63
c	3.9	3.96	2.3
d	2.4	1.7	0.65
	Mean air velocity, m/s		
a	0.09	0.1	0.22
b	0.04	0.23	0.32
c	0.08	0.05	0.14
d	0.08	0.38	0.43

However one should be kept in mind that the largest ventilation rates are not, a-priory, the best indicator for the ventilation performances of a greenhouse. Spatial climate heterogeneity inside greenhouse interfere with plants activity and influence largely crop behaviour through their effects on crop gas exchanges, particularly transpiration and photosynthesis.

In order to examine the homogeneity of the temperature distribution, we reduce the standard deviation of ΔT (temperature difference between inside and outside air) ($\sigma(\Delta T)$) by its means value ($\overline{\Delta T}$). The value for the above mentioned ratio was 1.22 for roof only openings, 3.83 for the combination of rood and side openings and at about 2 for the configurations with side openings. Consequently configuration c gives the best results concerning the homogeneity of temperature distribution and configuration d the worst results. The highest is the efficiency on the cooling, the lowest is the homogeneity of the temperature field and conversely.

5. CONCLUSIONS

The present results showed the importance of roof ventilation combined with sidewall ventilation for effective greenhouse ventilation. Results also showed that other parameters such as climate heterogeneity should be investigated in order to define the best ventilation configuration. CFD modelling is a powerful tool to help manufacturers to improve greenhouse designs and to adapt equipment to specific situations

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