Numerical Analysis of Buoyancy Driven Natural Ventilation in Multi-span Type Greenhouses

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Abstract

Computational fluid dynamics (CFD) analysis was used to study the best configuration of roof and side vents under buoyancy driven natural ventilation, which represents the most unfavorable situation for greenhouse cooling. A CFD model was validated and then used to compare ventilation with roof vents and combined roof and sidewall vents. The effects of the distance between opposing sidewall vents and the presence of simple roof vents were investigated and quantified. Combining roof and sidewall vents gave a ventilation rate per unit ground area that was 2 times higher than with roof vents alone in a 20 span greenhouse with a distance of 152 m between the sidewalls. In a 3 span greenhouse with 22.8 m between the sidewalls but with the same roof vent area per unit ground area, 7 times more ventilation was obtained with combined ventilation compared with only roof ventilation. These results prove that, with buoyancy driven ventilation, the contribution of the sidewall vents is important even for quite large greenhouses, but more critical for greenhouses with lower number of spans. It was concluded that to maximize ventilation when wind speeds are low, combined roof and sidewall ventilation should be used and that large greenhouses should be relatively narrow with a maximum distance between opposite sidewall vents of 50-60 m.

INTRODUCTION

In Mediterranean climate areas, in which cooling requirements are high during most growing cycles, it has been common practice to build long, narrow greenhouses of much less area than in northern Europe; the average area of a greenhouse in Almería is around 0.7 ha (Fernández and Pérez-Parra, 2005). However, recently, with the aim of limiting the entrance of pests, it has become quite common in many warm climate regions to build large greenhouses without sidewall vents. These greenhouses often have an insufficient area of roof vents which are then covered with low porosity anti-insect screens. Thus, the growers have problems in controlling excess temperature and humidity. This situation is most extreme when wind speeds are below 0.5 m s^{-1} (Bot, 1983; Papadakis, 1996) and natural ventilation is driven predominantly by buoyancy forces. In greenhouses of coastal areas this situation is common during the warm months, only in the hours before noon, but far from the coast these situations may be common during the central hours of the day, when the temperatures are higher.

Numerical analysis using CFD has already been used to study the role of greenhouse sidewall vents on the ventilation process. Mistriotis et al. (1997) performed a systematic analysis of natural ventilation in greenhouses a no-wind (and low wind-speed) conditions using a CFD code. His simulations confirmed the importance of side-wall ventilators for efficient thermally driven ventilation. However, only greenhouses of up to 4 spans width were analyzed. Kacira et al. (1998) performed simulations of ventilation in saw-tooth multispan greenhouses with two and four spans, and observed reductions in ventilation rates of between 80-90% at low wind speeds (0,5-2 m/s), when the windward sidewall vent was closed. Bartzanas et al. (2004) also found by CFD simulations that the combination of roof and sidewall vents, for windward ventilation was the best option to provide an optimal climate in a tunnel greenhouse.

With the aim of providing information on the influence of the physical characteristics of the greenhouse and ventilator location on ventilation rates, this paper used CFD to evaluate the effect of sidewall vents on buoyancy driven natural ventilation in multi-span parral type greenhouses. Ventilation rates, temperature fields and air speed profiles were calculated under zero-wind conditions and the effects of modifying the number of spans as well as the use of roof vents with and without sidewall vents.

MATERIAL AND METHODS

Theoretical background

A CFD code (Fluent, Ansys-Fluent Inc.) was used to perform the simulations to study the role of sidewall vents on buoyancy driven natural ventilation of greenhouse models generated in the program's pre-processor.

The program uses the finite volumes method to numerically solve the Navier-Stokes equations, this is, the mass, energy and momentum balances, permitting the calculation of air velocity and temperature fields:

$$\frac{\partial \Phi}{\partial t} + \sum_{i=1} \frac{\partial}{\partial X_i}(U_i \Phi) = \sum_{i=1} \frac{\partial}{\partial X_i}\left(\Gamma_\Phi \frac{\partial \Phi}{\partial X_i}\right) + S_\Phi \qquad (1)$$

where Φ represents the studied parameter, in our case, any of the three components of the air velocity vector or the temperature, Γ is the diffusion coefficient of parameter Φ, S_Φ the source term and U_i the velocity component. In order to account for gravity forces due to air density (temperature) changes, the Boussinesq hypothesis was used in the whole computational domain. This method treats density as a constant value in all the solved equations, except for the gravity term (thermal effect) of the momentum equation:

$$(r - r_0)g \approx -r_0 b\,(T - T_0)g \qquad (2)$$

where r_0 is the constant density of the flux, T_0 the real temperature and b the thermal expansion coefficient (for air at 20ºC, $b = 0.00329$). The Boussinesq approach is valid if the density (temperature) gradients occurring in the computational domain are not too large, this is, if $b(T-T_0) << 1$. In our case, with a naturally ventilated greenhouse, the temperature differences are never very large (<20 ºC), therefore the Boussinesq simplification can be applied.

To account for the pressure-velocity coupling and turbulence, the SIMPLE algorithm and the k-ε RNG model respectively, were used. The crop was not included in order to simulate a moment of very unfavorable conditions for the plants (just transplanted crop, negligible transpiration).

Greenhouses simulation models

A two-dimensional simulation model was created for an experimental parral type greenhouse 23.2 m long with 5, 7.6 m spans. The ridge height was 4.4 m and the gutter height 3.6 m. The greenhouse had one roof flap vent per span with dimensions 0.73 x 8.35 m. All roof vents were oriented in the same direction. There were rolling vents along the top of the two 23.2 m sidewalls, each with a maximum opening of 1.2 m. Taking the 5 span model as the reference model, additional models were created with 3, 7, 10, 15 and 20 spans, keeping the same dimensions for the spans and vents, and also their number and distribution per span.

The computational domain for the different greenhouse models was created with the following dimensions: 5 times the length of the greenhouse in the windward and leeward directions and 10 times the height of the ridge. The simulation models were meshed with a squared “pave” mesh scheme, with a cell size of 0.2 m inside the greenhouse and 0.4 m in the outside domain.

In order to simplify the calculations, a homogeneous temperature condition (330 K) was imposed on the soil (with sand mulch). The greenhouse walls were considered adiabatic.

RESULTS AND DISCUSSION

Validation of buoyancy driven natural ventilation simulations

With the purpose of validating the CFD simulation model for buoyancy driven natural ventilation, experimental data from Oca (1996) were used. The scale models ventilated by buoyancy through a simple rolling vent located on the lower part of one of the greenhouse sidewalls and a rolling roof vent, located near the ridge (Fig. 1).

Oca (1996) measured temperatures at different points over a cross section of a scale model located inside a larger closed greenhouse (soil, cover, air temperature, etc.) during one hour. This enabled the most important heat fluxes (convection between greenhouse soil and air) to be calculated (Table 1). The same author made three sets of measurements (E_1, E_2 and E_3) and calculated the average temperature difference between inside and outside the model around midday.

A 2D CFD model of this greenhouse was created using as boundary conditions the experimental measurements of Oca (1996) already given in Table 1. Table 2 summarizes the comparison of the average temperature difference data between CFD simulations and the experimental data from the field. Acceptable agreement is observed between the experiments and the simulations, with differences lower than 1 ºC.

Simulations of ventilation in parral multi-span greenhouses

The same boundary conditions, which corresponding to an average summer day in Almería, with a clear sky, no wind, around midday were used in all simulations.

Sidewall ventilation

Results of the simulations using combined sidewall and roof vents and only roof vents are presented in Table 3. It is clear that using sidewall vents significantly increase ventilation rates, expressed per unit area of greenhouse soil, compared to using only roof vents. Combined ventilation gave almost 3 times more ventilation than roof ventilation for the 15 spans model and 7 times more in the smaller 3 spans model. If the ventilation rates are normalized by the ventilator open area, combined ventilation was between 1.4 and 2.5 times more efficient than purely roof ventilation. This clearly shows that sidewall plus roof vents give better performance than roof vents alone.

The influence of sidewall vents on ventilation rate is reflected in the temperature fields produced inside the greenhouse. The results of simulations of the inside-outside temperature difference fields for the 5 span greenhouse model are shown in Fig. 2a (roof vents) and Fig. 2b (roof and sidewall vents). With roof vents, large temperature differences were found (> 4ºC) over almost all the greenhouse cross section, except in the fourth span through which the outside colder air was entering. To be more precise, over 32 % of the greenhouse cross section the temperatures were more than 4 ºC above the outside air temperature, with a maximum temperature difference of 9 ºC. Opening the sidewall vents dramatically changed the temperature pattern as shown in Fig. 2b. A flow of cold air entered the greenhouse through both sidewall vents producing a cooling effect, which for this width of greenhouse (38 m) covered almost the whole greenhouse. In this case only 16 % of the greenhouse cross-section (near the centre of the greenhouse) had an inside-outside temperature difference equal to or exceeding 4 ºC. Almost all the roof greenhouse vents evacuated the warmer, less dense air from inside the greenhouse.

Greenhouse size

Another important issue was to determine how buoyancy driven natural ventilation is affected by the area of the greenhouse. This was studied using the simulation models with 3, 5, 7, 10, 15 and 20 spans, both with the combination of sidewall and roof vents and with only roof vents. For these models the ratio of roof ventilator area to ground area covered remained constant whereas the corresponding ratio for the sidewall vents decreased with increasing span number. Figure 3 shows the how the ventilation rate varied with the number of spans.

It is clear that for combined ventilation, the ventilation rate decreased as the greenhouse size and distance between the sidewall vents increased. The data were fitted with an exponential decay function of $y = a + b/x^{0.5}$ (Fig. 3) for the ventilation rate (y) and the number of spans (x) of the greenhouse. When the number of spans became very large, the ventilation rate tended towards an asymptotic value. This value was very close to the ventilation rate with only roof vents which, as can be seen from Fig. 3, was almost independent of the number of spans and therefore of greenhouse size. This pronounced decrease agrees with the decrease observed by Kacira et al. (2004) for a similar vent configuration (sidewall vents and leeward roof vents) found in a gothic multi-tunnel greenhouse with wind driven natural ventilation, showing the importance of the role of sidewall vents both with and without wind.

CONCLUSIONS

Summarizing, with warm climate conditions being prevalent during most of the year, it is advisable to build greenhouses in which the distance between side vents, whether they are transversal or longitudinal to the dominant winds, does not exceed 50-60 m, to ensure their good contribution to natural ventilation processes, both with and without wind conditions (long and narrow greenhouses).

The presence of side vents is essential to ensure a good air exchange level under zero wind conditions, when the greenhouse natural ventilation relies on the temperature differences between air inside and outside the greenhouse, as can be observed on Table 3.

We can conclude, according to the results of the simulations, that the best strategy to ventilate the greenhouse, both with wind or with less favourable conditions, with zero wind, is to combine side and roof ventilation, to ensure a sufficient level of air exchanges.

Literature Cited

Bartzanas, T. , Boulard. T. and Kittas, C. 2004. Effect of vent arrangement on windward ventilation of a tunnel greenhouse. Biosystems Engineering, 88(4), 479-490.

Fernández, C. and Pérez-Parra J. J. 2004. Caracterización de los invernaderos de la provincia de Almería. Cajamar. 20pp

Kacira, M,. Short, T. H. and Stowell, R. R.1998. A cfd evaluation of naturally ventilated, multi-span, sawtooth greenhouses. Transactions of the ASAE, 41(3), 833-836

Mistriotis A., Arcidiacono C., Picuno P., Bot G P A. and Scarascia-Mugnozza G. 1997. Computational analysis of ventilation in greenhouses at zero- and low-wind-speeds. Agricultural and Forest Meteorology, 88, 121–135.

Oca, J. 1996. Study of buoyancy driven greenhouse natural ventilation using fluid flow visualization techniques in scale models Ph.D. Thesis, University of Lleida, Lleida, Spain

Tables

Table 1. Measurement conditions and heat fluxes during the first scale model experiments used as boundary conditions in the first set of validations.

	Experiment		
	E1	E2	E3
R_n (W m^{-2})	313	288	298
T_{ext} (ºC)	42	40.5	35.7

R_n: net radiation inside the scale model greenhouse
T_{ext}: average ambient temperature outside the scale model greenhouse.

Table 2. Average temperature differences between inside and outside the greenhouse scale model ($\Delta T = T_i - T_{ext}$) obtained experimentally and numerically by means of CFD simulations.

Average DT	**Experiment**		
	E1	E2	E3
ΔT experimental (Oca, 1996) (ºC)	4.2	4.3	4.5
ΔT CFD (ºC)	**4.6**	**4.3**	**4.3**

Table 3. Air exchange values expressed as air flow (m^3 s^{-1}), obtained numerically for six greenhouse models with increasing number of spans (3, 5, 7, 10, 15 and 20 spans) for the two studied ventilation configurations (sidewall + roof vents completely open and only roof vents completely open) .

	Air exchange values with combined ventilation (sidewall + roof vents)	**Air exchange values with roof ventilation only**
Number of spans	**m^3 s^{-1}**	**m^3 s^{-1}**
3 spans	15.2	2.2
5 spans	19.2	2.9
7 spans	25.1	4.5
10 spans	29.2	9
15 spans	31.4	11.5
20 spans	35.7	16.5

Figures

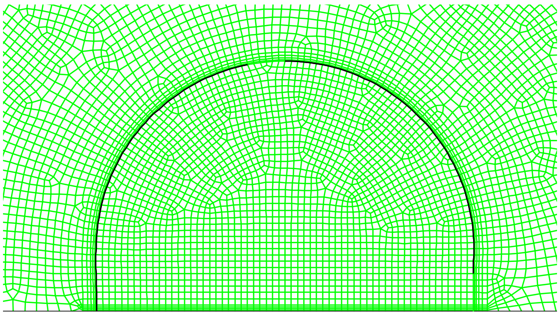

Fig. 1. 2D CFD model of the scale-model greenhouse used for the first set of validations.

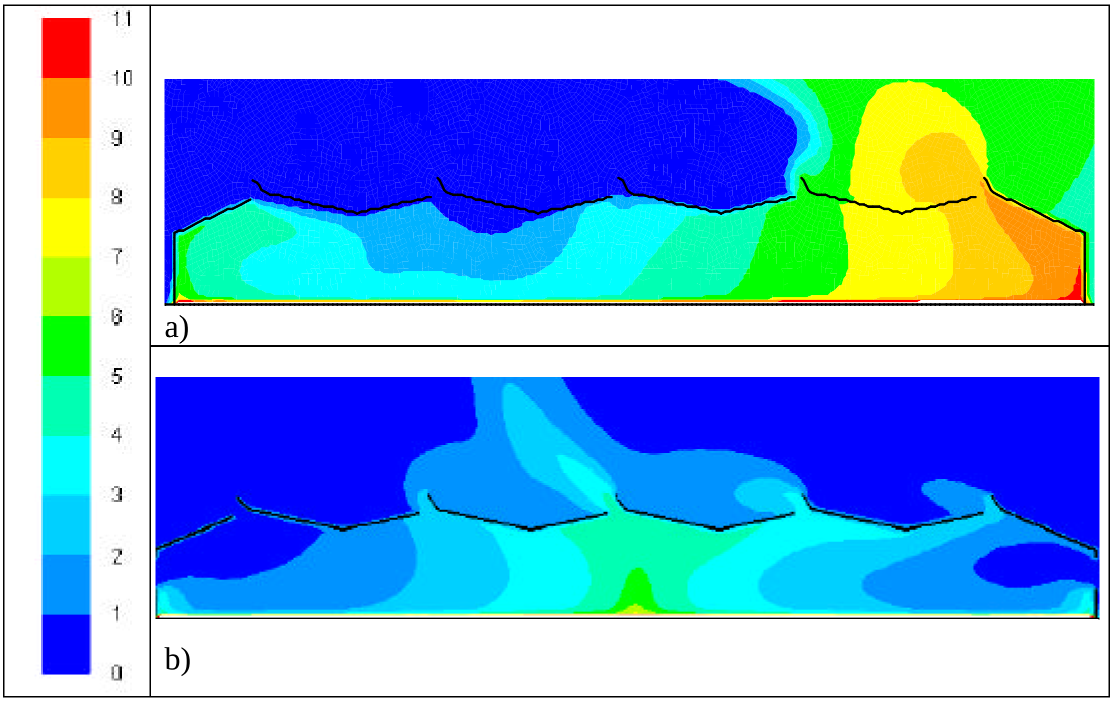

Fig. 2. Temperature difference scalar field (ºC) of the 5 spans greenhouse a) with roof ventilation b) with combined ventilation.

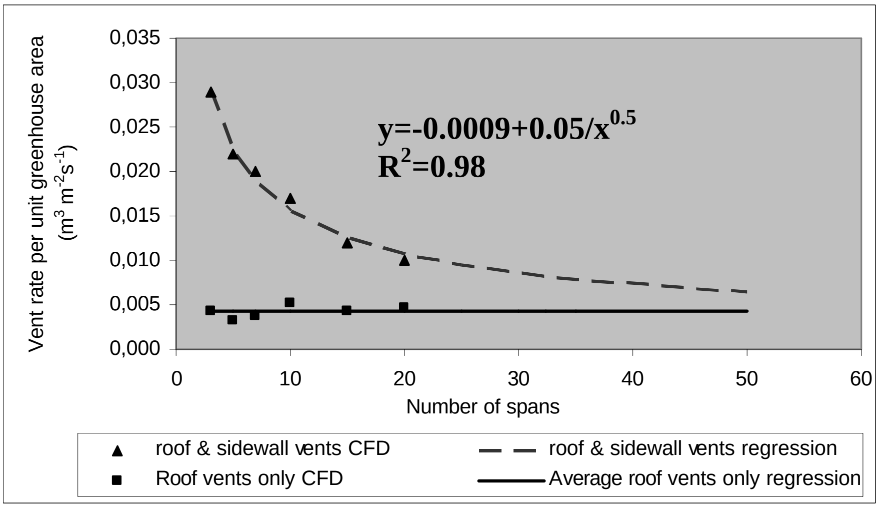

Fig. 3. Evolution of the ventilation flow per unit greenhouse covered area (m^3 m^{-2} s^{-1}) as the number of spans increases, for the configurations of roof ventilation only and combined roof + side ventilation.