Natural ventilation efficiency in a twin-span greenhouse using 3D computational fluid dynamics

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Abstract. In this work, a statistical analysis on greenhouse simulations to estimate the efficiency of natural ventilation in a commercial twin-span greenhouse is presented. A numerical simulation approach was adopted using the theory of three-dimensional computational fluid dynamics (CFD). With this approach, three-dimensional patterns for temperature and airspeed inside the greenhouse were generated, using specific boundary conditions. The CFD simulation was applied to an empty twin-span greenhouse with a floor area of 980 m^2 with low density polyethylene cover and two side continuous opening and one roof opening. The simulations assumed a sunny summer day with different airspeeds (0.0, 1.0, 2.0 and 5.0 m/s) in three directions for each non zero airspeed and three different temperature values for each airspeed (20.0, 25.0 and 30.0^{o}C).

Keywords: Computational fluid dynamics, natural ventilation, greenhouses.

1. Introduction

The main factors which characterize and influence the greenhouse environment are light, humidity, temperature, carbon dioxide concentration and ventilation rate. Ventilation is the main control method of the greenhouse's high temperatures. Natural ventilation is mostly used nowadays since it requires less energy, equipment and power than other forms of ventilation. The performance of ventilation plays an important role to the production, affecting not only the environmental conditions of the greenhouse, but the qualitative and quantitative properties of the crop product as well.

Most of the information which is available up to date on the effect of the factors that influence the internal climate and the production has been collected from sporadic experiments. Most experimental work was done on empty and small houses, isolated compartments and scale models. The reasons for not using large commercial greenhouses are the high cost in time and expense to conduct detailed measurements, the possibility of yield losses during large-scale experiments in operating greenhouses, the limited availability of commercial sized greenhouses for experimental work and the complexity of the measurements. The results from small-scaled greenhouse models experiments do not represent the actual behavior of a modern commercial greenhouse. In the current available literature there is not much information on the design of naturally ventilated greenhouses. Besides, the demand from the horticultural industry for useful information on the behavior of the greenhouse internal environment is increasing.

With the aid of computational flow dynamics, a simulation of real climate conditions and greenhouse structure details can be implemented, based on given conditions. Computational fluid dynamics (CFD) is a simulation approach that is used to study the behavior of all kinds of transport processes which involve fluid flow, heat and mass transfer. Its advantages over conventional experimental studies are the low cost and development time, the availability to study situations where experiments are not possible and the ease of performing a large range of parametric studies for optimization. Typical outputs from CFD simulations are spatial and temporal distributions of flow speed and direction, pressure, temperature and concentration. CFD has been applied in a large range of applications including chemical, automotive, aerospace, nuclear industries and food processing applications. Lately, CFD has been used in horticultural research for modeling the internal climate of greenhouses. Such models can then be used to study the dependence of the internal climate on external weather conditions and control strategies.

Reichrath and Davies (2002) have published a review paper that presents the state-of-the-art of the application of CFD for the modeling of greenhouses. Until now, CFD has been used for closed greenhouses (Boulard et al., 1999) and for greenhouses with natural ventilation (Mistriotis et al, 1997; Karcia et al., 1998; Lee and Short, 2000; Lee et al., 2000; Bartzanas et al., 2001). The influence of external climate (Brundrett, 1993; Miguel et al., 1997; Miguel et al., 1998; Bartzanas et al., 2001; Fatnassi et al., 2001), the number of spans (Reichrath and Davies, 2001), the presence of crops (Reichrath et al., 2000; Zhao et al., 2001; Roy and Boulard, 2004), the absence of crops (Boulard et al., 1993; Boulard and Baille, 1995; Reichrath and Davies, 2001) have been investigated on the internal climate of greenhouse.

In this work a statistical analysis on the efficiency of natural ventilation in a commercial twin-span greenhouse is presented. A numerical simulation approach was adopted using the theory of three-dimensional computational fluid dynamics (CFD). With this approach, it was able to generate three-dimensional patterns for temperature inside the greenhouse, using specific boundary conditions. The statistical analysis was applied for an empty twin-span greenhouse with the same characteristics and computational parameters as those used by Pontikakos et al. (2005). The greenhouse has a floor area of 980 m^2, low density polyethylene cover and two side continuous and one roof openings.

Temperature data of the entire greenhouse environment were generated by CFD simulations and the obtained results were analyzed in order to find the cases that were statistically significant on natural ventilation efficiency. The simulations assumed a sunny summer day with four different airspeeds (0.0, 1.0, 2.0 and 5.0 m/s) in three directions for each no zero airspeed (North-South, South-North and West-East) and three different external temperature values for each airspeed (20.0, 25.0 and 30.0^{o}C). The statistical results could be useful for the greenhouse's design and for prediction purposes. The continuation of this work will focus on inclusion of specific types of cultivation crop inside the greenhouse.

2. Materials and methods

2.1. Mechanisms Affecting Natural Ventilation Airflow

Ventilation is caused by pressure difference across the opening due to thermal effect and wind forces. Natural ventilation is complex and greenhouse design is more difficult than fan ventilation. This phenomenon is induced by external wind force (wind effect) and buoyancy force (thermal effect) based on the temperature rise (temperature difference between internal and external air). Natural airflow inside greenhouses is a combination of the effects of both thermal and wind forces. Natural ventilation rate varies linearly with external wind velocity and area of ventilation openings, while it also varies linearly with the square roots of height of openings and temperature rise (Roy et al, 2002).

- *Thermal effect*

When two openings are at different heights and the indoor temperature is higher than the outside, a pressure gradient is generated causing the inside air to move out of the higher openings and the outside air into the lower openings. The airflow in this case is dependent on the temperature difference between inlet and outlet as well as the aperture difference in height.

- *Wind Forces*

The difference in dynamic wind pressure creates a potential for the air to flow from a point to another point where the pressure is lower (Givoni, 1981). When wind strikes a wall perpendicular to its direction of flow, the surface of the wall experiences pressure higher than that of the atmospheric pressure. This pressure difference causes the indoor air to flow from inlet/s to outlet/s located in building walls at lower surface pressure. In addition, even when the measured pressure difference between the two apertures is equal to zero, some airflow can still occur as a result of inertia from wind entering the window (Ernest, 1991; Evans, 1979) or from differences in pressure along the height of each window.

2.2. CFD

2.2.1 Principles

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. Its advantages over conventional experimental studies are substantial reductions in lead times and development cost, availability to study systems where experiments are not possible and ease of performing a large range of parametric studies for optimization.

The computational domain, in which a CFD simulation will take place e.g. the greenhouse plus its environment, must be well defined. This domain is divided into small cells, the control volumes, in each of which a value for the simulated variables (e.g. temperature, airspeed) is calculated and conservation principles (equations) are applied to each of these control volumes. Rate equations define the transfer rate of a transportable property. The computational effort required can be large and is dependent on the number of computational cells in the domain, the number of variables solved in each cell and the kind of simulated transport processes. Details of the basic equations and numerical method of CFD are widely available in the literature (Patankar, 1980; Hunt, 1995; Versteeg and Malalasekera, 1995).

2.2.2. Governing Equations
The used CFD code (Airpak, 2002) solves the Navier-Stokes equations for transport of mass, momentum, species, and energy when it calculates laminar flow with heat transfer. RNG k-ε transport equations (ReNormalisation Group) (Yakhot and Orszag, 1986) are solved when the flow is turbulent and the Discrete Ordinates (DO) Radiation equations (Raithby and Chui, 1990; Chui and Raithby, 1993) for radiative heat transfer.

2.3. Greenhouse characteristics
An empty twin-span greenhouse (Figure 1) with a floor area of 980 m^2 with low density polyethylene cover, two side continuous openings and one roof opening was used. The greenhouse characteristics are presented in the Table 1 and are the same used by Pontikakos et al. (2005).

3. Results
3.1. CFD simulations
Airpak 2.10 Fluent Inc. software was used for this study. Tree-dimensional simulations were carried out and all were steady-state. Both buoyancy and thermal effects were considered. The ground characteristics were considered to be dynamic and the air was assumed real and not an ideal gas. The simulation assumed a sunny summer day with four different air speeds (0.0, 1.0, 2.0 and 5.0 m/s) in three directions for each no zero airspeed (North-South, South-North and West-East) and three different temperature values for each airspeed (20.0, 25.0 and 30.0^{o}C). In particular, in all simulations the computational domain was large enough to eliminate side effects of the boundaries on the pressure distribution around the greenhouse. The size of the computational domain was much larger than the greenhouse (Figure 2).

Table 1. Greenhouse characteristics

Scale	No scale Continuous roof vent Continuous side openings
Ridge height	4.2 m
Gutter height	3.0 m
Width	14.0 m
Length	70.0 m
Roof vent width	1.10 m
Roof Vent pivot point	4.2 m
Roof vent opening angle	19^o
Side opening width	1.12 m
Latitude	37.58^o
Longitude	23.32^o
Orientation	East-West (parallel to greenhouse length)
Ground emissivity	0.9
Cladding material	Low density poly-ethylene (LDPE)
Cladding thickness	10^{-4} m
Cladding visible transmittance	0.75

Source: Pontikakos et al. (2005)

At the outlet boundary, a fixed static pressure condition was chosen, being in relation to the ambient value. The RNG turbulence model was used since it was proven to give good results for internal flows in greenhouses (Mistriotis et al., 1997). The grid was an unstructured hexahedral mesh with higher density at the near wall regions around and inside the greenhouse. The CFD simulation numerical parameters are presented in Table 2.

Internal temperature data of the entire greenhouse environment were generated by means of CFD simulations and the obtained results were statistically analyzed. Figure 3 displays plane cuts for the greenhouse internal temperature.

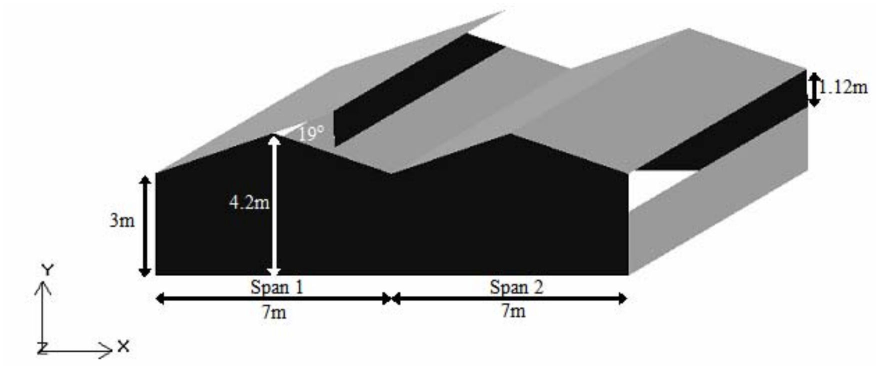

Figure 1. The three-dimensional greenhouse

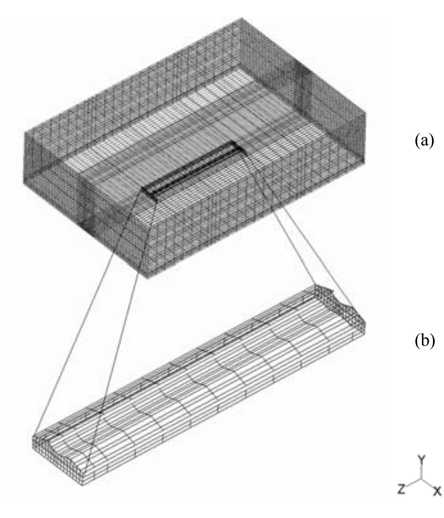

Figure 2. The computational domain (a), enlarged view of the greenhouse (b)

Table 2. CFD simulation numerical parameters

CFD simulation numerical parameters	
Mesh size	Width x Height x Length=114m x 40m x 170m
Turbulence model	RNG model
Outer boundary pressure	Fixed
Outer boundary temperature (T_0)	Fixed: Cases:20°C, 25°C, 30°C
Outer boundary airspeed (U_0)	Fixed: Cases: 0.0m/s, 1.0m/s, 2m/s, 5m/s
Outer boundary airspeed directions (D)	Fixed: North-South (NS), South-North (SN) and West-East (WE)

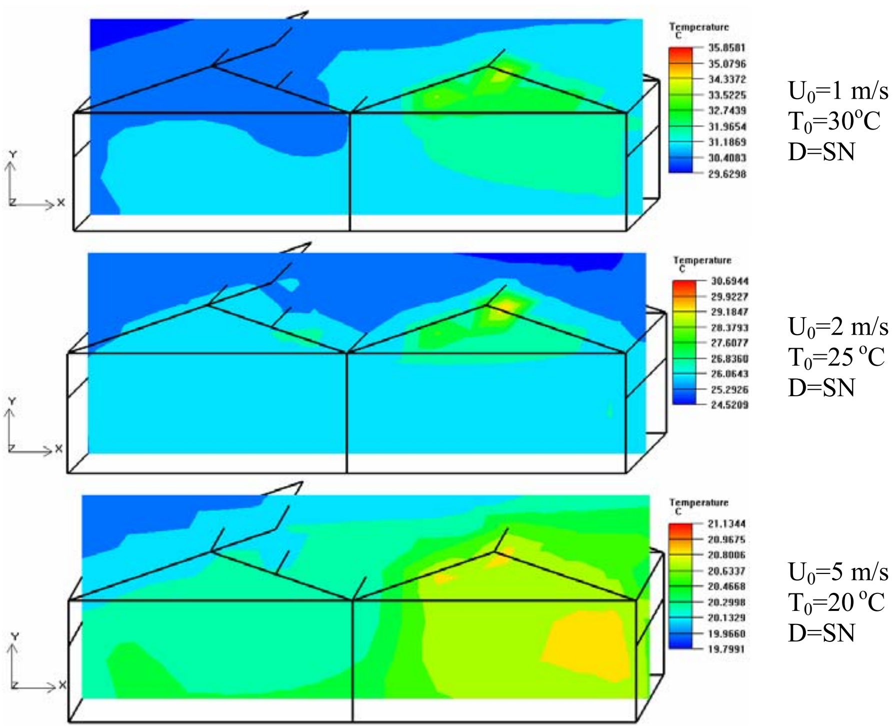

Figure 3. Plane cuts for the temperature and airspeed velocity.

3.2. Statistical analysis

The program STATGRAPHICS Plus 5.1 for Windows was used for the statistical analysis of CFD data. The statistical models that were developed are depicted in Table 3 and their accuracy is shown in the last two columns of the table.

In Table 4, twenty-three homogenous groups are identified using letters, among the thirty different cases. The levels containing the same letter denote that there are no statistically significant differences. The method that was used to discriminate among the means is Tukey's honestly significant difference (HSD) procedure. With this method, there is a 5% risk of calling one or more pairs significantly different when their actual difference equals zero.

Table 3. The equations of the fitted models for internal temperature

Boundary airspeed direction	The equation of the fitted model for internal temperature	R^2	P value
No direction (nD)*	$1.12633 + 1.00313\ T_0 + 0.0628887\ SPAN$	98.1275%	0.00**
South-North (SN)	$0.955425 + 1.00053\ T_0 - 0.140007\ U_0 - 0.0591079\ SPAN$	99.7737%	0.00**
North-South (NS)	$0.442496 + 1.00505\ T_0 - 0.209373\ U_0 + 0.606219\ SPAN$	98.8933%	0.00**
West-East (WE)	$1.32774 + 0.998023\ T_0 - 0.219597\ U_0 + 0.162969\ SPAN$	99.2418%	0.00**

* For boundary airspeed with zero value.
**Since the P-value for each estimated model is less than 0.01, there is a statistically significant relationship between the variables at the 99% confidence level.

5. Conclusions

Internal temperature data of the entire greenhouse environment were generated by CFD simulations and the obtained results were analyzed in order to find the cases that were statistically significant on natural ventilation efficiency. This analysis could be useful for the greenhouse's design and for prediction purposes particularly in the case of the presence of some specific cultivation crop in the greenhouse. The continuation of this work will include specific types of cultivation crops inside the greenhouse.

Statistical results showed that the external boundary temperature is a crucial parameter on the pattern of the internal greenhouse temperature. In addition, for specific external temperatures and wind directions, airspeed becomes the crucial parameter. Finally, the statistical models that were developed, have very low computational and time demands, in comparison to the original CFD simulation model and can be used for real-time estimation of temperature and airspeed patterns of the greenhouse environment.

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Table 4. Multiple Range Tests for Internal Temperature (T) by T0, U0 and D. Method: 95.0 percent Tukey HSD

Case	Outer boundary temperature (T_0) (°C)	Outer boundary airspeed (U_0) (m/s)	Direction (D)	Internal temperature (T) (°C)	Homogeneous Groups
1	20	5	SN	20.2039	a
2	20	5	NS	20.3935	b
3	20	5	WE	20.4072	b
4	20	2	SN	20.4976	c
5	20	1	SN	20.8085	d
6	20	2	NS	20.8878	e
7	20	2	WE	21.0141	f
8	20	1	NS	21.1788	g
9	20	0	ND	21.3027	h
10	20	1	WE	21.4405	i
11	25	5	SN	25.2157	j
12	25	5	NS	25.3988	k
13	25	5	WE	25.4155	k
14	25	2	SN	25.5045	l
15	25	1	SN	25.8342	m
16	25	2	WE	26.0566	n
17	25	1	WE	26.2133	o
18	25	2	NS	26.2394	o
19	25	0	ND	26.2492	o
20	25	1	NS	26.2521	o
21	30	5	SN	30.2097	p
22	30	5	NS	30.4040	q
23	30	5	WE	30.4212	qr
24	30	2	SN	30.4910	r
25	30	1	SN	30.8252	s
26	30	2	NS	30.9138	t
27	30	2	WE	31.1602	u
28	30	1	WE	31.2210	uv
29	30	1	NS	31.2938	v
30	30	0	ND	31.3340	w

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