Numerical Simulation of Natural Ventilation in Greenhouses: a Comparison between Finite Volumes Method and Finite Elements Method

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Abstract

Modelling of greenhouse climate published to date has used several computer fluid dynamic programs based on the finite volumes method (FVM). Although few commercial packages are based on the finite elements method (FEM), this has also been successfully used to model the wind and structure interaction in greenhouses. However, no comparison has been made of the codes solving the same equations governing natural ventilation of greenhouses (benchmark test), and the goal of the present contribution is to compare the numerical results calculated with a FVM program (Fluent v. 6.1.) and FEM software (ANSYS/FLOTRAN v. 9.0.). Although the equations are similar, the handling of the boundary conditions, the interpolation functions, and other numerical techniques such as the use of pressure or the iteration scheme are different. Simulation results have been compared with experimental observations in two different cases: i) a reduced-scale single-span greenhouse with adiabatic walls was used to compare airflows and temperature distributions and ii) air exchange rate was measured in a four-span experimental greenhouse for low wind velocities and temperature gradients. The simulated results for temperature and dynamics fields are compared with the experimental measurements with respect the meshing facilities, convergence time and the initial set of state variables. Based on this benchmark test in two dimensions, recommendations are provided for the use of each method.

INTRODUCTION

Convective heat and mass transfers dominate the exchange processes in ventilated greenhouses (Roy et al., 2002) and govern the indoor environmental parameters such as temperature, humidity and CO_2 content (Boulard et al., 2002). The most important numerical techniques to discretise the fluid continuum include finite differences, finite elements and finite volumes (Norton et al., 2007). However, due to the difficulties for programming and implementing finite elements few commercial packages are currently available (Norton et al., 2007). Conversely, for their accessibility, finite volumes are the most commonly used numerical techniques in CFD modeling, mainly for greenhouse ventilation (Fatnassi et al., 2006). This paper compares 2D numerical simulations performed with CFD codes using a Finite Volumes code (Fluent) and a Finite Elements code (ANSYS/FLOTRAN). The simulation results are compared with each other and with experimental observations performed for two greenhouse types under two different experimental conditions (Boulard et al., 1998-1999; Lamrani et al., 2001; Fatnassi et al., 2006).

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MATERIALS AND METHODS

Experimental Arrangement

1. Reduced-Scale Single Span Greenhouse. This involves free convective flows in a half-scale test cell (2.2 × 2 m) simulating the absorption of solar radiation at the floor surface of a single-span greenhouse (see the tested configurations in Table 1). Temperatures were measured with thin thermocouples and velocities measured by laser Doppler anemometry (Boulard et al., 1998, 1999; Lamrani et al., 2001) were used for validation of the CFD simulations.

2. Multi-Span Greenhouse (922 m^2) in Sophia Antipolis (France) with roof vent and side openings and insect-proof screen (anti bemisia nets) was also simulated with CFD. For validating the simulations, real air exchange rate measurements using N_2O as tracer gas were performed in the experimental greenhouse (Fatnassi et al., 2006) for different roof and side opening characteristics and two wind directions (Table 1).

Numerical Model

1. Discretisation Scheme. The finite volumes (FV) method subdivides the domain into a finite number of control volumes (CV) and uses the integral form of the equations, applying conservation laws locally to CV. Surface and volume integrals are approximated using suitable quadrature formulae, obtaining an algebraic equation for each CV, in which a number of neighbouring nodal values appear (Ferziger and Peric, 2002). In complex geometries it is often not possible to have a good quality FV mesh over the entire domain (Peric, 1990; Lehnhauser and Schafe, 2003; Zhu et al., 2004).

In the finite elements (FE) method the functions are approximated locally over each element by continuous functions, which are uniquely defined in terms of the values of the function (and possibly its derivatives) at the nodes of each element. The distinguishing feature of FE methods is that the equations are multiplied by a weight function before they are integrated over the entire domain. Galerkin's method of weighted residuals was used to form the element integrals (Zienkiewicz, 1977). Basically, FEM tries to minimize the residual projection (integral) in the subspace formed by a set of weighting functions.

2. Calculation Procedures. In this study, the closure procedure for turbulence modelling is the κ–ε model (Launder and Spalding, 1974). Segregated solving techniques, such as Semi-Implicit Method for Pressure-Linked Equations (SIMPLE), were used by the two software packages to determine the pressure field indirectly by closing the discretised momentum equations with the continuity equations in a sequential manner (Patankar and Spalding, 1972).

The driving force of the natural convection in greenhouses is the buoyancy force arising from small temperature differences within the flow. There are two main methods of modelling the density variations that occur due to buoyancy. The first one is the well-known Boussinesq approximation (Ferziger and Peric, 2002) that has been used successfully in many greenhouse applications (Boulard et al., 2002; Fatnassi et al., 2004). However temperature dependency of density can also be expressed by means of the ideal gas equation. This more complex method may provide an accurate description of the density variations within the flow regime, but can also generate convergence difficulties for CFD solutions (Foster et al., 2002).

3. Boundary Conditions. The computational grids of the CFD software used Cartesian coordinates and a finer resolution was imposed in critical portions of the flow subject to strong gradients (wall boundary layers and the mixing regions). The dynamic boundary conditions prescribed wall-type boundary conditions along the floor, the walls and the roof surfaces of the greenhouse model.

For the reduced-scale greenhouse the thermal boundary conditions imposed fixed temperatures at roof and floor levels (Table 1), adiabatic conditions along the side walls of the scale greenhouse model together with null pressure gradient and fixed temperature at the domain limits.

A logarithmic wind profile (with 0.0195 m roughness) was imposed 25 m from the multispan greenhouse. The insect proof nets protecting the side and roof openings were considered porous media. For the multispan greenhouse, the top of the domain was considered the symmetric limit of the flow (null vertical velocity) and outlet boundary conditions were automatically computed to satisfy continuity conditions at the leeward limit of the domain (Fatnassi et al., 2006).

RESULTS

Multi-Span Greenhouse

In the first case analysed with windward roof and side opening vents, simulations indicated that air enters through the first roof vent and the side opening, and leaves the greenhouse through the other two roof vents (Fig. 1). Air loops appear inside the greenhouse spans and above the gutters. The main difference observed in the simulated airflow patterns with both discretisation methods is that according to FVM (Fig. 1a) the inside air loops are clockwise, whereas according to FEM they are anti-clockwise (Fig. 1b). In the second case with leeward roof and without side opening vents, FVM and FEM simulations indicated that air enters through the first roof vent and comes out through the other two roof vents. Comparison of measured and simulated air exchange rates (Table 2) highlights the better precision of the air exchange rate computations when using the FVM. FEM simulations give similar results with windward roof vents but the ventilation rate is considerably lower with leeward roof vents.

Reduced-Scale Single Span Greenhouse

For both configurations analysed (single-sided roof vent and two symmetrical roof vents), incoming air streams through the lower section of the openings swept over the greenhouse walls in a large convective loop before breaking out through the upper sections of the openings (Fig. 2). Both discretisation methods accurately represent the airflow patterns with a single rotating air loop inside the greenhouse. In the two cases analysed, the shape of the convective loop and the mean simulated components of the air velocity and temperature were generally in good agreement with the experimental results. However, for FVM simulations a vertical temperature gradient was observed from heated floor to cool air entering throughout openings (Fig. 3c), although the simulated temperatures in the centre of the greenhouse generally agree with experimental values (Table 3). This difference between simulated (Fig. 3c) and observed temperature distributions (Fig. 3a) for case 1, when temperature simulated by FVM in the centre is better than simulated by FEM, emphasises the necessity to use several points of measurement to validate the CFD models.

DISCUSSION

Compared to FVM, FEM is less computationally efficient in terms of speed for the two greenhouses analysed. Generally FVM calculation took half the time-step necessary for FEM simulation. However, this advantage is counterbalanced by the increased number of nodal points needed for meshing a domain of complex geometry (Ahmad et al., 1998). In FEM the convergence depends mainly on the solver chosen for temperature, while in FVM it is proportional to the domain size.

Before starting simulation, the user must provide FVM with initial values for selected variables in the domain. It is recommended to initialize the flow field to the values at the inflow. This facilitates the solution search process starting from these initial values. However, FVM shows great sensitivity to the initial values of velocity when airflow is exclusively generated by buoyancy effect.

FEM allows easier meshing of objects of arbitrary shape than FVM (GAMBIT). This original advantage of using FEM, is currently offset by the systematic mesh refinement approach of the FVM, which can also handle the complex geometry through structured and un-structured meshes. However, in complex geometries, such as the multi-span greenhouse, it is often not possible to obtain good meshing quality over the entire domain. The process of space division in finite volumes can produce an overlap among the different greenhouses zones or generate regions without meshing. FEM has some limitations in satisfying mass conservation equation. In this case we use a double line (Fig. 1b) to define a boundary inside the computational domain (greenhouse roof and walls) to ensure the continuity of the flow and to prevent unreal flow through the greenhouse cover, which considerably complicates the description of the geometry of the CFD model. With FEM it is possible to describe directly a profile for speed and turbulence parameters.

CONCLUSIONS

In summary, this work provides elements for one of the first CFD benchmark tests for natural greenhouse ventilation calculations in two dimensions. Two methods have been used for solving the conservation equations, based on either a finite volumes (FV) technique or a finite elements (FE) formulation. The two numerical techniques have been compared with respect to two greenhouse types and two test cases. The air exchange rate, velocities and temperatures have been compared with experimental results obtained with different methods (tracer gas technique and laser Doppler anemometry), showing good overall agreement, but with major discrepancies in some cases.

Both numerical methods provide similar qualitative descriptions of the airflow in the two greenhouses (the reduced scale mono-span module and the multi-span), but for multi-span greenhouse with leeward ventilation the FEM simulated lower ventilation rate. On the whole, FVM converges more quickly than FEM.

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Tables

Table 1. Boundary conditions for the two greenhouse types studied.

Parameter	Case 1	Case 2	Units
Reduced-scale single span greenhouse			
Convective flux from the soil	275	300	W m^{-2}
Inside surface soil temperature	48.6	46.5	°C
Outside air and soil temperatures	19.7	19.3	°C
Covering material temperature	28.4	26.3	°C
Multi-span greenhouse			
Wind direction	WW	LW	-
Outside wind speed at 5.9 m	1.60	1.53	m s^{-1}
Side vent open	Yes	No	-
Outside temperature	29	32	°C
Outside radiation	749	801	W m^{-2}
Convective flux in the cover	45.0	48.0	W m^{-2}
Surface soil temperature	34	36	°C

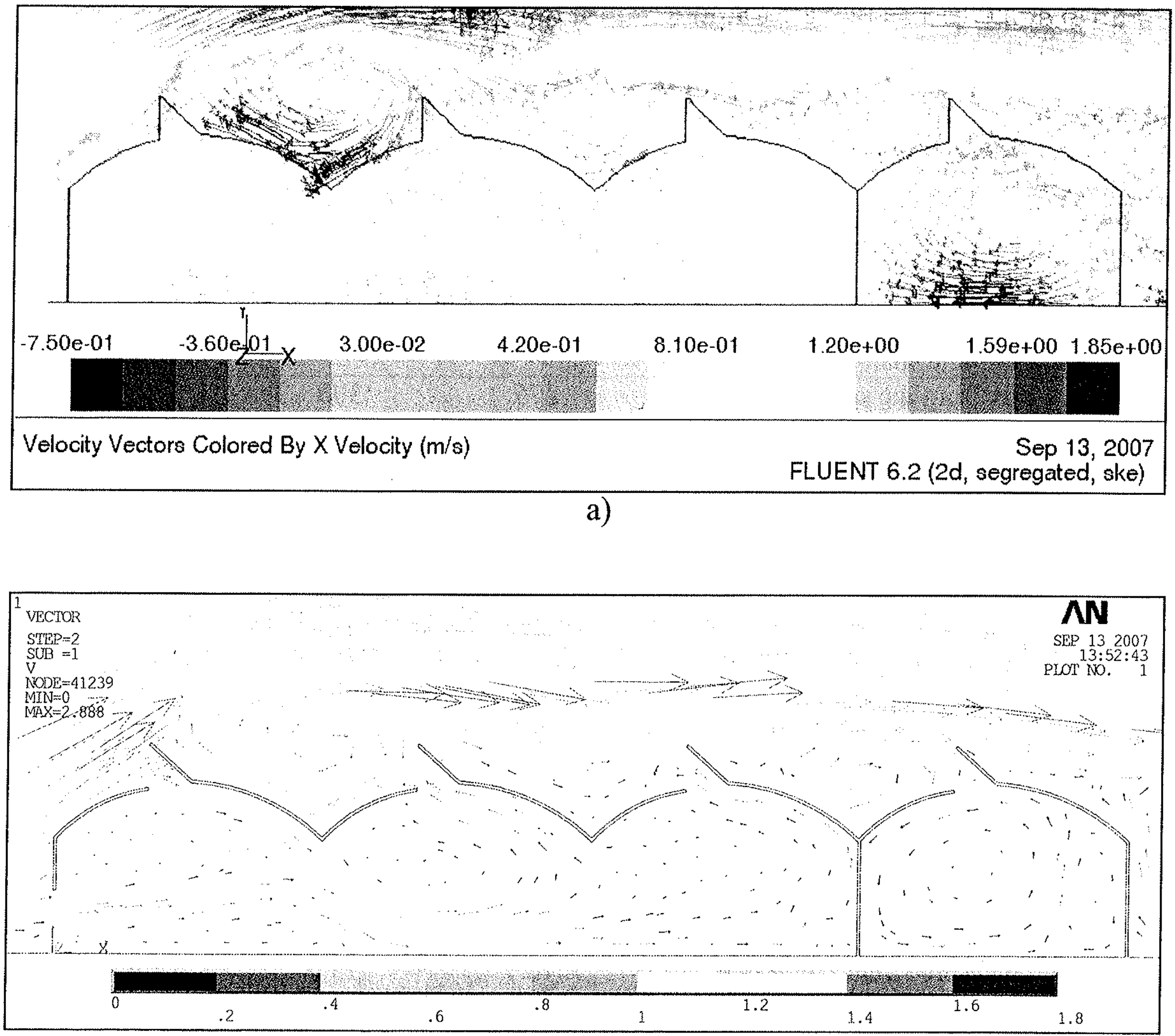
Table 2. Values of temperature in the centre of the multi-span greenhouse and ventilation rate measured (Fatnassi et al., 2006) and simulated with CFD.

Parameter	Case 1	Case 2	Units
Experimental measured ventilation rate	13.7	13.6	h^{-1}
Simulated ventilation rate with FVM	10.3	12.1	h^{-1}
Simulated ventilation rate with FEM	16.9	2.7	h^{-1}
Experimental measured temperature	18.0	19.4	°C
Simulated temperature with FVM	18.0	20.0	°C
Simulated temperature with FEM	17.2	18.3	°C

Table 3. Values of temperature in the centre of the reduced-scale greenhouse measured experimentally (Boulard et al., 1998-1999) and simulated by the Finite Elements Method (FEM) and with the Finite Volumes Method (FVM).

Method of measuring temperature	Case 1	Case 2	Units
Temperature measured with thermopiles	31.3	27.5	ºC
FEM. Flux constant in the floor	27.2	28.5	ºC
FEM. Temperature constant of the floor	26.5	25.4	ºC
FVM. Flux constant in the floor	40.9	21.6	ºC
FVM. Temperature constant of the floor	31.7	30.4	ºC

Figures



a)

b)

Fig. 1. Airflow pattern in a four-span greenhouse for a windward configuration with a wind speed of 1.6 m s^{-1} (case 1) simulated with: a) FVM and b) FEM.

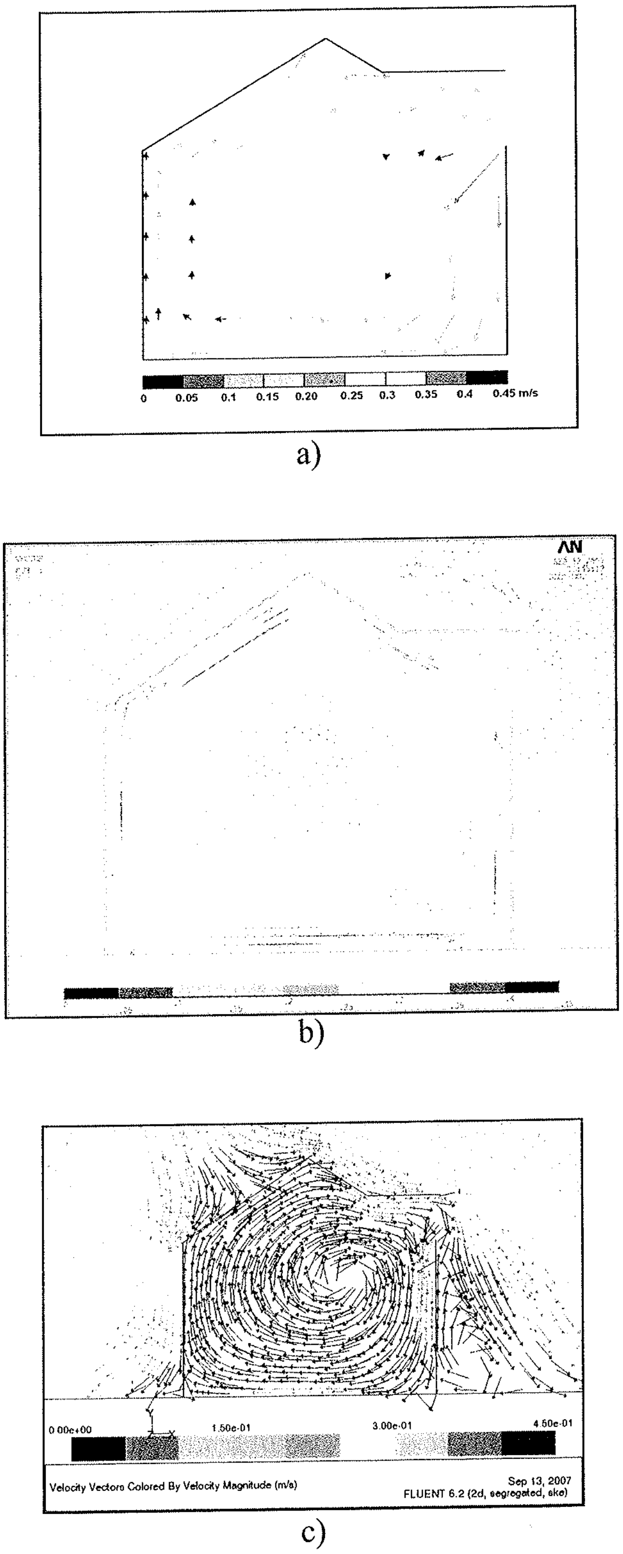


Fig. 2. Airflow pattern in a reduced-scale single-span greenhouse for a flux in the soil of 275 W m^{-2} (Case 1): a) velocities measures by laser Doppler anemometry (Boulard et al., 1998-1999); b) velocity simulated with FEM and f) velocity simulated with FVM.

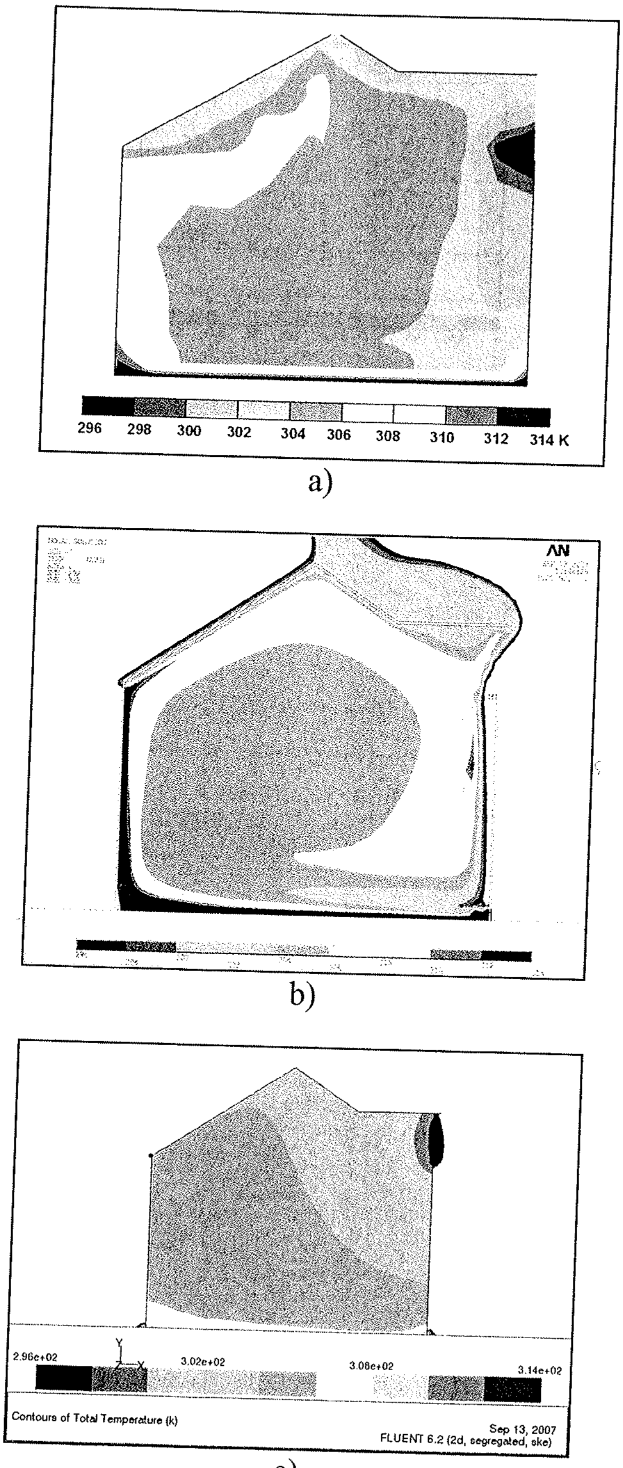


Fig. 3. Temperature distribution in a reduced-scale single-span greenhouse for a flux in the soil of 275 W m^{-2} (Case 1): a) temperature measured with thermocouples (Boulard et al., 1998-1999); b) temperature simulated with FEM and c) simulated with FVM.