African Journal of Biotechnology Vol. 10(77), pp. 17651-17662, 5 December, 2011
Available online at http://www.academicjournals.org/AJB
DOI: 10.5897/AJB10.2488
ISSN 1684–5315 © 2011 Academic Journals

Review

Computational fluid dynamics in greenhouses: A review

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Accepted 11 November, 2011

Computational fluid dynamics is a tool that has been used in recent years to develop numerical models that improve our understanding of the interaction of variables that make up the climate inside greenhouses. In the past five years, more realistic studies have appeared due mainly to the development of more powerful software and hardware. However, it is necessary to perform an analysis to show us the trends, strengths and weaknesses in the use of this tool. In this study, we reviewed the state of the art of CFD in studies of airflow and climate inside greenhouses, analyzing the most important issues that help us understand how it has evolved, as well as trends and limitations on their use.

Key words: Airflow, CFD, greenhouse, turbulence, porous media.

INTRODUCTION

Ventilation is a process that determines the climate inside a greenhouse due to its effect on mass and energy exchange with the outside. The overall goal of precision agriculture is to make cultural operations more efficient, reduce environmental impact while enhancing crop quality and yields (Mercado-Luna, 2010). To assess whether ventilation is efficient, it is important to consider the behaviour of climate variables and their role in crop development.

Airflow and its influence on the variables that make up the climate create a dynamic in temporal and nonlinear behaviour, which can be expressed by using a system of second-order differential equations so complex that it does not have an analytical solution. The last decade has seen an increase in the use of numerical methods such as Computational Fluid Dynamics (CFD), which based on the Navier-Stokes equations, has proved to be a good tool for developing models that help us understand relationships between variables that make up the climate and behaviour of airflow in the ventilation of greenhouses.

In the past five years, many studies have used CFD to investigate the conditions inside greenhouses. CFD has been able to increase the degree of realism by incorporating insect-proof screens and simulation of the crop through its incorporation as a porous medium, among others in 3D models. The results have been able to improve our understanding of the phenomenon of greenhouse ventilation (Figure 1). Paper reviews have been made to visualize the trends on the use of CFD in greenhouses, however despite great effort, there are lack of studies aimed at analyzing trends in the use of CFD to tell us the importance of adding more realism to the simulations, as is the response of crops and their interaction with the variables that define the climate inside the greenhouse.This review discusses significant recent studies to understand how the use of CFD has evolved.

Fundamental CFD equations

Computational fluid dynamics is based on the governing fluid dynamics equations (continuity, momentum and energy). The equations obtained directly from the volume or fixed element in space is known as "conservative form". While the equations obtained directly from the volume or move with the fluid element are called "non-conservative form". The substantial derivative is physically the exchange

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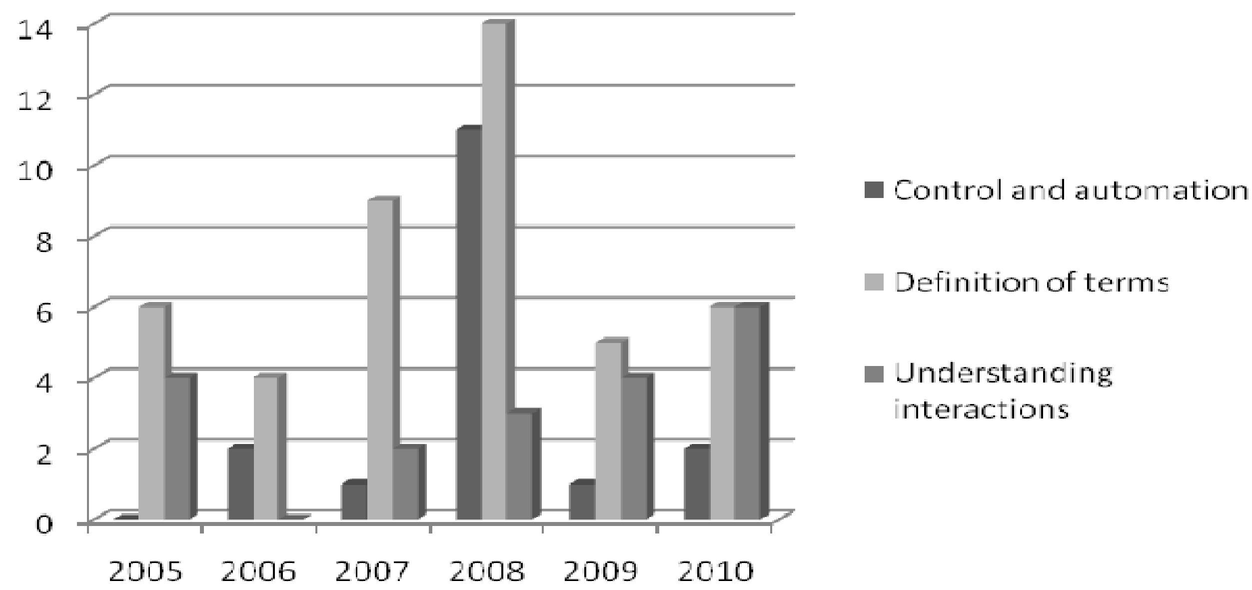

Figure 1. Proportion of studies based on justification.

rate of any substance that moves with a fluid element. It consists of two parts; the first part is called the local derivative, which is physically the rate of change over time in a fixed point. The second part is called the convective derivative, which is physically the exchange rate due to movement of the fluid from one point to another in the field of fluid, where the fluid properties are spatially different. The resulting material can be applied to any field variable fluid, for example: pressure (p) or temperature (T) Anderson, 1995).

$$\nabla \equiv i\frac{\partial}{\partial x}+j\frac{\partial}{\partial y}+k\frac{\partial}{\partial z} \qquad (1)$$

$$V \equiv (u, v, w)$$

$$\frac{\partial}{\partial t}\iiint_V \rho dV + \iint_S \rho V \cdot dS = 0 \qquad (2)$$

$$\rho\frac{Du}{Dt} = -\frac{\partial p}{\partial x}+\frac{\partial t_{xx}}{\partial x}+\frac{\partial t_{yx}}{\partial x}+\frac{\partial t_{zx}}{\partial x}+\rho f_x$$

$$\rho\frac{Dv}{Dt} = -\frac{\partial p}{\partial x}+\frac{\partial t_{xy}}{\partial x}+\frac{\partial t_{yy}}{\partial x}+\frac{\partial t_{zy}}{\partial x}+\rho f_y$$

$$\rho\frac{Dw}{Dt} = -\frac{\partial p}{\partial x}+\frac{\partial t_{xz}}{\partial x}+\frac{\partial t_{yz}}{\partial x}+\frac{\partial t_{zz}}{\partial x}+\rho f_z \qquad (3)$$

$$\rho\frac{D}{Dt}\left(e+\frac{V^2}{2}\right) = \rho q + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)-\frac{\partial(up)}{\partial x}-\frac{\partial(vp)}{\partial y}-\frac{\partial(wp)}{\partial z}$$

$$+\frac{\partial(ut_{xx})}{\partial x}+\frac{\partial(ut_{yx})}{\partial y}+\frac{\partial(ut_{zx})}{\partial z}+\frac{\partial(vt_{xy})}{\partial x}+\frac{\partial(vt_{yy})}{\partial y}+\frac{\partial(vt_{zy})}{\partial z}$$

$$+\frac{\partial(wt_{xz})}{\partial x}+\frac{\partial(wt_{yz})}{\partial y}+\frac{\partial(wt_{zz})}{\partial z}+pf\cdot V \qquad (4)$$

1) Continuity Equation
2) Momentum Equation (a non-conservative)
3) Components in x, y and z
4) Energy Equation (a non-conservative)

The equations form a coupled system of partial differential nonlinear equations. So far no analytical solution has been found. It is commonly assumed that the fluid is an ideal gas where the intermolecular forces can be neglected. For an ideal gas equation of state:

$$p = \rho RT \qquad (5)$$

Where, R is the specific gas constant. For a calorically ideal gas we have:

$$e = CvT \qquad (6)$$

Where, Cv is the specific heat at constant volume (Rodríguez, 2006; Norton et al., 2007).

APPROACHES USED IN THE APPLICATION OF CFD TO THE GREENHOUSE ENVIRONMENT

CFD is used to design facilities with the objective of suitable climatic conditions. According to Sase (2006), within a mild climate, appropriate design and control of ventilation are required to ensure effective cooling and uniformity of environment. It is possible to design an optimal greenhouse by calculating the area, volume and vent area, as well as the material properties of the roof (Impron et al., 2007). Rico-García et al. (2006), comparing two different greenhouses, showed the importance of geometry and determined that the ventilation rate for a greenhouse with large vertical roof and windows was better than for a multi-span greenhouse. Omer (2009) describes various designs of low energy Greenhouses. In agreement with Baeza et al. (2008), various design changes such as size and shape of vents, can improve air movement in the area of crops. More also, Bakker et al. (2008) investigated energy balance, determining that the amount of energy used per unit of output is defined by improvements in energy conversion, environmental control to reduce energy consumption and efficiency of agricultural production. Furthermore, in a study of outdoor areas using the turbulence model Reynolds-averaged Navier-Stokes equations (RANS), van Hoff (2010) found that small geometric modifications can increase the ventilation rate up to 43%. The performance of ventilation in enclosed spaces is affected by the flow of outside air, type of cover, height of the installation and the ventilation opening (Kim et al., 2010). Computational parametric studies on greenhouse structures can help identify design factors that affect greenhouse ventilation under specific climatic conditions (Romero et al., 2010).

Windward and leeward wind direction

Wind direction outside the greenhouse is an important factor in defining the flow of air and climate inside the greenhouse. The boundary conditions of wind speed distribution are deduced from experimental data and wind direction with respect to the longitudinal axis of the greenhouse, which can range from 0 to 90°. Roy and Boulard (2005) simulated the impact of wind at 45 and 90°, showing the influence of wind direction in the air velocity, temperature and humidity distributions inside the greenhouse; a similar result was found by Campen (2008). Rico-García et al. (2006) also showed that a greenhouse with large vertical roof windows works better with a windward condition, whereas the multi-span greenhouse works better with a leeward condition. So, wind direction affects the level of ventilation. In a study by Khaoua et al. (2006), four different openings of roof vents obtained ventilation rates between 9 and 26.5 air exchanges per hour for the windward and 3.7 to 12.5 on the leeward wind condition, respectively, which can maintain acceptable and uniform climate conditions for particular cases where the wind is perpendicular to main axis of the greenhouse. Overhead ventilation to the windward and leeward directions represents a reduction in the ventilation rate by 25 to 45%, compared with only opening to the windward direction (Bournet et al., 2007).

Openings to the windward direction generate the highest rate of ventilation; however, the greatest homogeneity of the temperature and wind speed arises from combining windward and leeward roof vents (Bournet and Khaoua, 2007). Kacira et al. (2008) showed that the air temperature inside the greenhouse was higher on the windward side than on the leeward side when roof vents were used. Wind speed had a linear influence on air exchange rates, while the wind direction did not affect them. Majdoubi et al. (2009) observed a strong wind air current above a tomato canopy that was fed by a windward side vent and a slow air stream flowing within the tomato canopy space. The first third of the greenhouse until the end of the leeward side was characterized by a combination of wind and buoyancy forces, with warmer and more humid inside air that was evacuated through upper roof vents. There may be a conflict between increasing ventilation and improving uniformity because there is little information on air movement affecting the cooling efficiency and the uniformity of the environment (Sase, 2006). These same studies have been reported by Burnet and Boulard (2010).

Heat exchange tube and natural ventilation

Rouboa and Montero (2007) simulated with a CFD model the effects on temperature and wind speed of the introduction of hot water pipes along a greenhouse in nighttime conditions, under three shapes: Natural convection heating (case A), artificial heat pipes (case B) and artificial heat pipes and natural ventilation (case C) by using the turbulence model. Re-Normalization Group (RNG) observed an average increase in air temperature to 2.2 C, 6.7 and 3.5°C; the turbulence was lower for case A, slightly increasing with the heating system for case B and higher for case C, due to the effect of natural ventilation.

Forced ventilation

The study of fluid dynamics in ventilation systems application provides elements of natural ventilation. A numerical investigation by Rousseau (2008) on a prototype air-forced unit for crop growth chambers obtained simulations that verify a nonlinear relationship between airflow rate and opening vents, showing the mixing zone. The

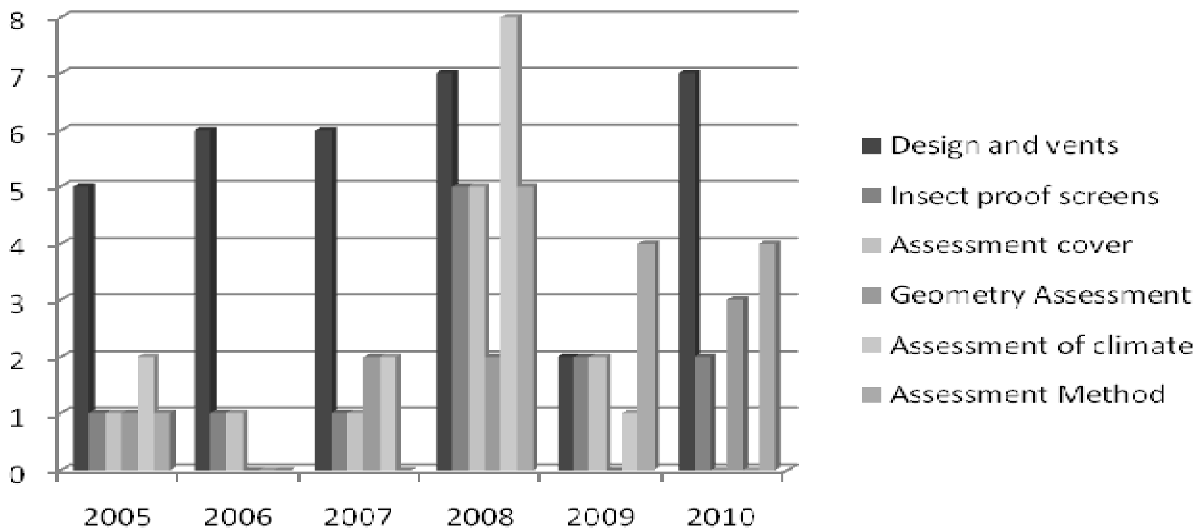

Figure 2. Proportion of studies based on their objectives.

use of a device air flow deflector below the roof vents proved to increase air exchange in the area of cultivation effectively. According to the CFD simulations, the combination of the side vent dual configuration has little effect on overall air exchange, but it increases air movement in the crops and homogenizing temperatures (Baeza et al., 2008). Another investigation by Hughes and Ghani (2010) took into account the effect of the external angle of the ventilation device (Windvent) louvers against the internal pressure and velocity to optimize the device performance. The optimum angle was 35 to 40° with a wind velocity of 4.5 ms^{-1}.

Fog-cooling System

According to Sase (2006), in a fog-cooled greenhouse in combination with natural ventilation, air cooled by fogging above the plants is likely to go down. Kim et al. (2007) developed a CFD model to simulate air temperature and relative humidity distribution in a greenhouse with fog-cooling systems, regardless of the presence of plants. Air temperatures and simulated measures ranged from 0.1 to 1.4℃ and relative humidity differences were 0.3 to 6.0%. The results showed that the best cooling system performance occurs when fog nozzles are within 2.3 m of the floor and 1.9 m of the side walls with a uniform spacing of 3.7 m and the best location for the injectors is at the entrance of the side openings of the greenhouse.

Screens and vents

Recent research using CFD includes further refinement in adaptive meshing areas to maintain a high level of accuracy during modelling and make predictions more reliable (Norton and Sun, 2006) (Figure 2). Screens reduce ventilation rate by 33% according to a study by Kittas et al. (2005). In accord with Harmanto et al. (2006), using different sizes of screen over the vent opening has a significant effect, reducing 50 to 35% mesh 40, 78 and 52 and causing a temperature gradient of 1 to 3℃ with a mesh of 52 as optimal for a tropical greenhouse. Majdoubi et al. (2007) found that insect-proof screens significantly reduced airflow, increasing thermal gradients inside the greenhouse by 46%. Using a wind tunnel with screens of different porosity (0.62, 0.52 and 0.4), Teitel et al. (2008a) showed that a screen inclined by airflow reduces drag compared to a flow perpendicular to the screen, allowing an increase of 15 to 30% and 25% in the upper compared with a flat screen. Once more, Teitel et al. (2009) found that higher speed screens are inclined at 45° and decreased to 135° tilt.

In addition, Ali et al. (2009) investigated the effect of roof vents on the temperature and coefficient of heat transfer in naturally ventilated facilities. Better flow patterns and heat transfer from the heated ceiling are observed when the front opening is located closest to the ceiling and the rear opening is located closest to the centre. The increase in temperature and humidity as a result of insect-proof screens is particularly evident in the vicinity of the crop canopy (Majdobi et al., 2009). Another study by Romero et al. (2010) found that a larger roof vent area can greatly enhance ventilation, while the extension of an insect-proof screen on side walls hardly changes the air exchange rate.

Solar radiation and temperature

Some studies have used solar radiation and transpiration models based on the heat and water balances of the crop

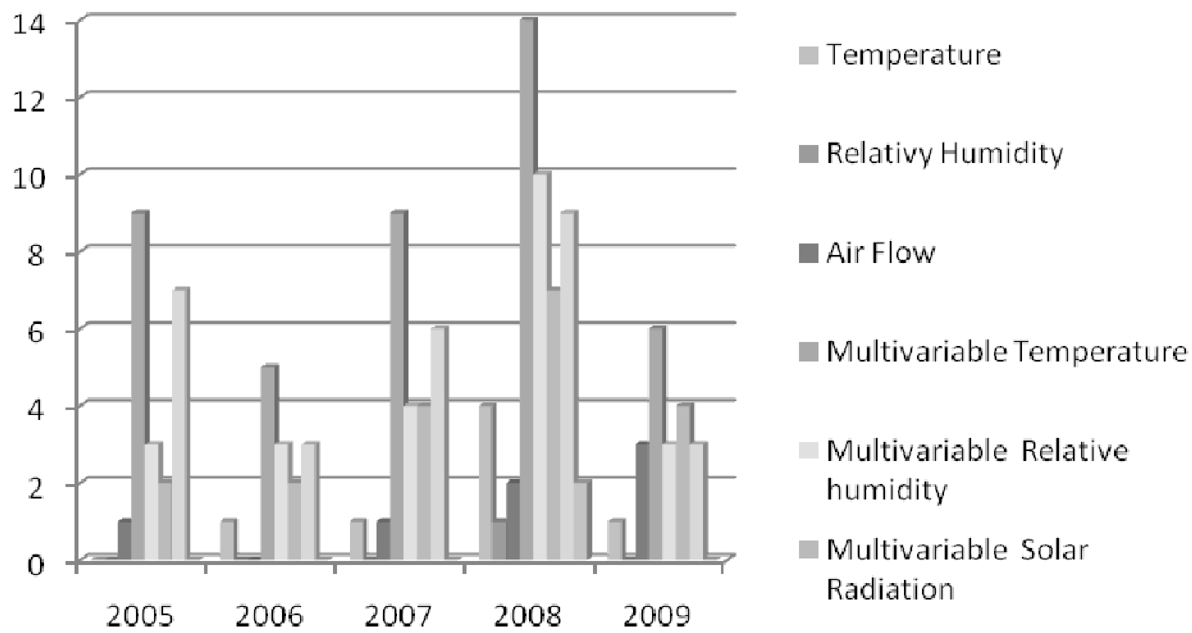

Figure 3. Proportion of variables studies.

to investigate the distributions of air temperature and humidity and the interactions between the crop and the air, in addition to the airflow distribution (Sase, 2006) (Figure 3). In accord with Tablada (2005), the factor of solar protection plays a crucial role in maintaining stable thermal conditions indoors, even if the outside air temperature is higher. The slightly higher air speed on the top floor is insignificant in view of reducing the negative effect of the solar radiation over the roof and facade. The temperature of the greenhouse cover is an essential parameter needed for any analysis of energy transfer in the greenhouse. A sub-model developed by Impron et al. (2007) calculated the transmission of radiation through the greenhouse, including the reduction of NIR transmission through the roof. Tong et al. (2009) developed a numerical model to determine time-dependent temperature distributions based on hourly measured data for solar radiation, indoor air, soil and outside temperature, taking into account variable solar radiation and natural convection inside the greenhouse during the winter in northern China.

Temperature and air exchange

The effect of solar and thermal radiation is often taken into account by setting specific wall or heat fluxes at the physical boundaries of the greenhouse. Radiative transfer within the crop itself is still the major concern since it determines the two main physiological crop functions: transpiration and photosynthesis. This challenge is now launched and will probably receive much attention within the next few years (Bournet and Boulard, 2010). Pontikakos et al. (2006) analyzed data obtained from a CFD model, showing that the external boundary temperature is a crucial parameter in the pattern of internal greenhouse temperatures and that for specific external temperatures and wind directions, airspeed becomes the crucial parameter. According to Molina et al. (2006), opening vents affect the air flow, the ventilation rate and the air temperature distribution in a greenhouse; where the mean air temperature at the middle varied from 28.2 to 32.9°C with an outside air temperature of 26°C, there were regions inside the greenhouse that were 13°C warmer than the outside air. Nebbali et al. (2006) used a semi-analytical method to determinate the ground temperature profile from weather parameters and other characteristics, to help in evaluating heat flux exchange between the surface and the air. Furthermore, Rico-García et al. (2008) show that ventilation in greenhouses due to the temperature effect produces high air exchange rates; however, those air patterns occur near the openings, causing almost no air exchange in the central greenhouse area due to a stagnant effect that reduces the wind effect throughout the greenhouse. In agreement with the results of Majdoubi et al. (2009), convection and radiation are the dominant forms of heat transfer. The measurements show that the difference between the air temperature inside and outside the greenhouse is strongly linked to solar radiation and secondly to wind speed. However, Chow and Hold (2010) obtained the following conclusions from studying buoyancy forces from thermal gradients:

1. Thermal radiation without air participation alters air temperature distribution by radiating upper zone thermal energy in the wall towards the lower zone wall, which

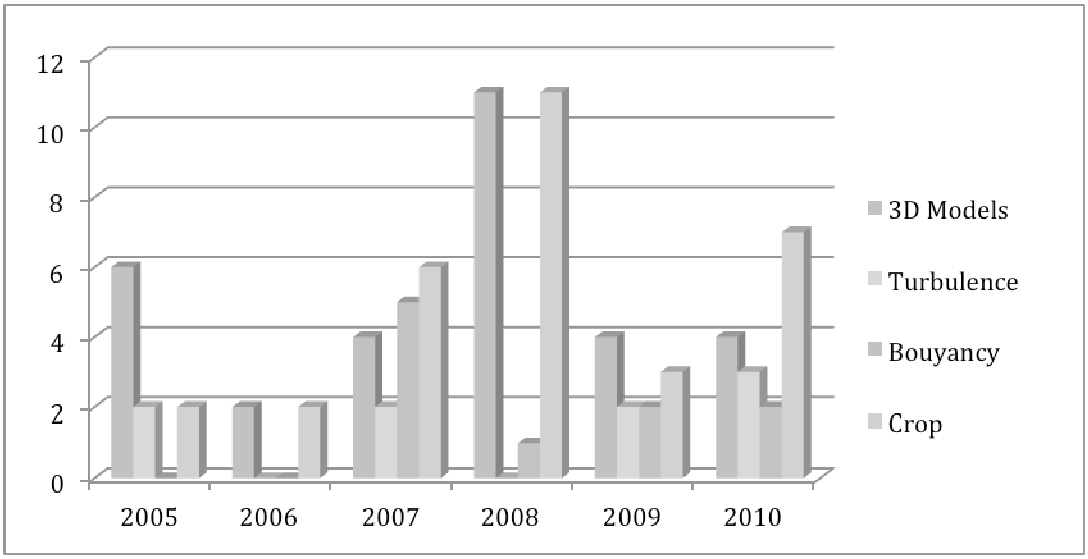

Figure 4. Degree of realism and accuracy

then affects air temperature through conduction and convection.
2. The inclusion of air absorption increases the effect of radioactive thermal redistribution by allowing air to absorb and radiate heat, reducing temperature gradients further.
3. Thermal boundary conditions and heat loads affect the predicted absolute temperature bounds, but do not affect the temperature distribution.

Radiation conditions play an important role in redistributing heat. Atmospheric conditions, especially relative humidity, are important for the calculation of radiation and heat transfer.

Turbulence and buoyancy

As computing power has increased, so has the sophistication of CFD packages (Figure 4). According to Norton and Sun (2006), the standard k-ε turbulence model commonly used in some cases provides inadequate results, and the choice of turbulence models must be based on the phenomena involved in the simulation. Different turbulence models cause differences in speed, temperature and humidity patterns, confirming the importance of choosing the model that most closely matches the actual conditions of turbulence (Roy and Boulard, 2005). Teitel and Tanny (2005) showed that the output of the turbulent heat flux is mainly due to cold air entering the greenhouse, which produces hot and cold eddies that enter and leave the greenhouse. Roy and Boulard (2005) showed the effects of wind direction on climate parameters inside the greenhouse are usually simulated with the use of different turbulence models available, to determine the energy balance between the flow of perspiration and the flow of radiation. Under ventilation parameters based on Bernoulli's theorem, Majdoubi et al. (2007), showed that bad ventilation performance is not a result of the low value of the greenhouse wind–related ventilation efficiency coefficient, but rather the low rate of discharge due to pressure drop in air flow is generated both by the use of anti-insect screens with small openings as an obstruction due to the orientation of the rows of crops. Moreover, Rouboa and Montero (2007) noted that the RNG turbulence model is best suited to simulate microclimates in arc greenhouses.

According to Baxevanou et al. (2007), the circulation of air buoyancy effect shows the importance of internal temperature gradients, forced convection resulting from natural ventilation predominates. Rico et al. (2008) indicated that applying temperatures as the main driven forces for the buoyancy effect provides a simple way to study ventilation and inner air patterns. Vera et al. (2010a) observed that differences in temperature and ventilation rate strongly influence the movement of air, pushing it through openings where space is colder, while creating rising air currents when it is hot. Majdoubi et al. (2009) showed that the buoyancy forces induced by air temperature and increased humidity result in loops of air between the crop and the zenith windows, which in turn tend to accelerate the pace of evacuation of heat and water vapour, enhancing indoor climate. Fidaros et al. (2010) studied turbulence in Greece; they found that external temperature variation is very important because internal temperature is determined by convection induced by the input current. The housing area had a higher circulation in the centre of the greenhouse near the deck and in the corners of the ground, where the effect of the input current is weak. Defraeye et al. (2010) used a RANS turbulence model by CFD to evaluate heat transfer by forced convection at the surface of a cube immersed in a turbulent boundary layer for applications in the atmospheric boundary layer (ABL), where wind speed is not disturbed at a height of 10 m. In a study of airfoil wakes, three turbulence models were simulated by Roberts and Cui (2010); the Reynolds Stress Model (RSM) is superior over the k-ε model, and when a time-dependent solution is necessary, LES is the desired option. However, LES does require the airfoil geometry to be included in the domain because it performs poorly when given only inlet velocities, turbulence kinetic energy and eddy dissipation at the trailing edge of the airfoil. According to Bournet and Boulard (2010), although they have been used for a long time in both the agriculture and environment studies, less empirical approaches to turbulence based on the use of LES have never been applied to greenhouse climate modelling and could perhaps be used to look for a solution to this complex situation.

Inside buildings, it is difficult to maintain a thermally stratified space with low ceilings, such as in offices and homes. Vera et al. (2010b) studied buoyancy in enclosed spaces, drawing the following conclusions:

1. Rising air currents and the exchange of humidity are closely related to the temperature difference between the lower and upper space. Low temperature in the upper space promotes the exchange of humidity and air flow through the opening; the hotter it is, the greater the restriction of air and humidity transport.
2. The existence of upward air currents when the space is warmer than the bottom is caused by local conditions such as non-uniform temperature distributions in the upper space and convective warm currents of the base and the humidity source.
3. Compared with patients without mechanical ventilation, ventilation severely restricts the flow of air through the opening.

The main difficulty in the choice of the model is that greenhouse systems cover a range of length and velocity scales that generally require different modelling approaches (Bournet and Boulard, 2010).

Incorporation and crop modelling

The effect of plants on greenhouse ventilation has also been studied previously. Bournet et al. (2007), based on studies by Nederhoff (1985) and Lee and Short (1998), assumed that a crop of 90 cm high and low density decreases between 12 and 15% to ventilation. They concluded that Representative Plant Temperatures (RPTs) can be calculated instead of measured. Roy and Boulard (2005) developed a 3D model for the characterization of climatic conditions in a greenhouse, incorporating five rows of ripe tomatoes as a porous medium where the buoyancy, heat and moisture transfer between the crop and air flow inside were considered. The heat and moisture transfer coefficients are deduced from the characteristics of the laminar boundary layer of the leaf, which is calculated with the velocity of flow in the crop. Khaoua et al. (2006) found that under external conditions of 1 ms^{-1} air velocity and 30° of temperature, wind speed at crops varies according to the modalities of ventilation from the windward 0.1 and 0.5 ms^{-1} for the leeward side, while temperature differences range from 2.0 to 6.1°C. In a study with tomatoes, Majdoubi et al. (2007) found that crop rows oriented perpendicular to air movement reduced the rate of airflow through the cultivation in a greenhouse by 50%. According to Baeza et al. (2008), a greenhouse with natural ventilation efficiency must combine a sufficient number of air changes to remove excess heat, with good circulation of air through the crop. The effect of the crop was also evaluated by Impron et al. (2007) by a sub-model to determine the effects of ventilation, the properties of the cover, and crop transpiration. In agreement with Kruger and Pretorius (2007), the temperature and velocity at the plant level are influenced by the arrangement and number of windows.

Furthermore, a study by Sapounas et al. (2007) simulated a tomato crop with a porous medium, taking into account the addition of buoyancy to develop a model of the pressure drop of air flow due to the crop. The model depended on the area leaf stage of growth and cultivation, under the RANS turbulence model in conjunction with the RNG k-ε turbulence model. The results, validated with experimental measurements obtained at 1.2 m in the canopy showed that the evaporative cooling system is effective with numerical parameters, providing a useful tool to improve system efficiency. A study by Roy et al. (2008) on leaf level through an experimental setup based on Münger cells measured the temperature, relative humidity and different heat flows to the leaves of soybeans, obtaining minimum stomatal resistance values ranging from 66 to 200 sm^{-1}. Teitel et al. (2008b) built a small-scale model and found that wind direction significantly affects the ventilation rate and temperature distribution in crops. Moreover, a study by von Elsner et al. (2008) on the effect of near-infrared (NIR) reflecting pigments in microclimate and plant growth found that a temperature drop up to 4°C in a young crop is the result of a 18% reduction in the transmission of global radiation in spring. At the same time, during the rainy season, minimizing transpiration differences in temperature and shading reduces water requirements in the plants, and they observed parthenocarpic fruit rot and yield-reducing crop. In a tunnel-type greenhouse, a tomato crop was modelled by Bartzanas et al. (2008) by designing a porous medium, where they emphasize the influence of the heating system on greenhouse microclimate. The climatic behavior of the rows of the tomato crop is taken into account using external user defined functions (Baxevanou et al., 2007). According to Majdoubi et al. (2009), reorienting crop rows in simple ways improved climatic

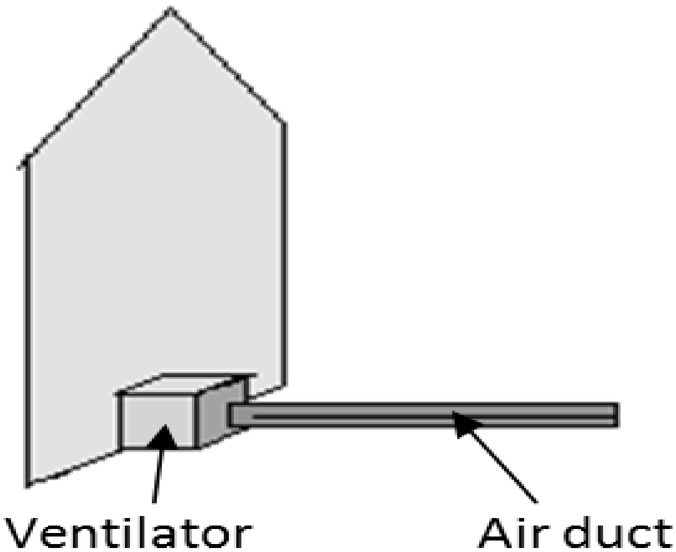

Figure 5. Schematic diagram of the system in which the ventilator is located at the sidewall of the greenhouse, drawing in outside air and distributing it via ducts (Campen et al., 2008).

conditions. Endalew et al. (2009) performed CFD modelling of a plant with leaves and branches of the canopy, using turbulent energy equations in porous sub-domains created around the branches. Fidaros et al. (2010) simulated a greenhouse tomato crop as a porous medium to model radiation transport by discrete ordinates (DO). According to Teitel et al. (2010), when applying the porous medium approach, the Forchheimer equation is often used, which can cause erroneous results with respect to the pressure drop through screens. An alternative way is to calculate it through several panels of porous media used to simulate screens with realistic geometries. Moreover, the crop exerts a mechanical strain (drag force) on the flow just above, but also interacts through the transpiration process with the temperature and humidity distributions (Bournet and Boulard, 2010). A simple model of transpiration of a crop was developed by Sun et al. (2010), who related it to the characteristics of ventilation in a greenhouse in eastern China, obtaining a good approximation. In general, there have been enormous efforts devoted to the analysis of ventilation in greenhouses (Norton, 2007); each new study provides new elements not only in the movement of air in the greenhouse but also in the forms it takes due to interactions occurring in the environment, such as position, shape and size of windows, and (one of the most important), the presence of a crop (Flores, 2010).

Humidity

Roy and Boulard (2005) simulated wind directions of 0, 45 and 90° with respect to the orientation of the greenhouse to determine wind speed, temperature and humidity distributions inside the greenhouse, getting a good approximation for the humidity. In agreement with Demrati et al. (2007), models allow estimation with better accuracy of water requirements for a banana crop under cover and improved water saving in regions where water is the main limiting factor for agriculture. Roy et al. (2008) studied moisture on the surface of leaves at low light levels; crop transpiration and air flow were integrated into a single parameter model of leaf stomatal response to air flow and radiation. Campen (2008) showed (Figure 5) that climate through a ventilation system is more homogeneous and the control is more efficient than with the conventional method of steam extraction. Dehumidifiers and cooling reduce the overall difference in humidity between the middle and lower areas of a greenhouse. And as demonstrated by Kim (2008), using a 3D model could identify the heterogeneous distribution of relative humidity in a greenhouse. According to Majdobi et al. (2009), an increase in air temperature precedes a more moderate increase in specific humidity.

MODELS AND EXPERIMENTAL VALIDATION

According to Sase (2006), recent progresses in CFD techniques have accelerated a more detailed analysis of air movement in combination with verification tests (Figure 6). However, studies in this area have been necessary to address the detailed design of each element involved in climate, highlighting the difficulty involved in the analysis of air movement inside a greenhouse (Flores, 2010). The quality of the results is often deduced from the agreement with experimental data. Nevertheless, no standard procedure exists to really assess the accuracy of the simulations, and the type of comparison often differs from one study to the next (Bournet and Boulard, 2010).

The use of porous media models to simulate the pressure drop across flow boundaries, such as insect screens and fences, is very popular and must be validated experimentally. New technologies such as particle image velocimetry have worked well to complement predictions; field solutions may include biological responses increasing the realism of the simulations (Norton et al., 2007). According to Rouboa and Monteiro (2007), improvements could be achieved by incorporating night-time transpiration and optimizing the size of the mesh elements to lower computation time. Recent progress offers the opportunity to build a grid that fits the physical boundaries of the structures studied much more realistically than a Cartesian structured grid, and closely follows the contour of the solid boundaries. However, they require verification of the meshing quality to obtain accurate data and computational convergence (Bournet and Boulard, 2010).

Statistical models

The statistical models developed by Pontikakos et al.

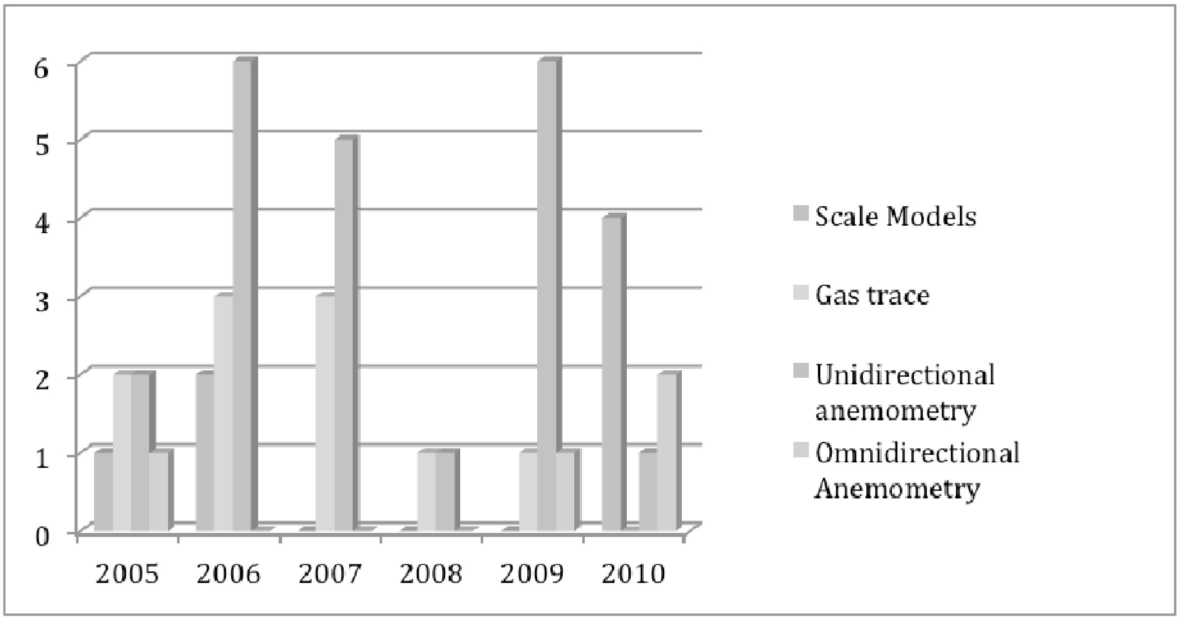

Figure 6. Proportion of experimental validation studies.

(2006) are less computationally expensive than the original CFD model, and they can therefore be used for real-time estimates of temperature and flow rate in a greenhouse.

Model types

In a small-scale model developed by Teitel et al. (2008b), wind direction significantly affected the ventilation rate and temperature distribution in crops. Chen et al. (2010) evaluated seven types of models (analytical, empirical, experimental small-scale, pilot-scale, multi-area network, zone model and CFD) to predict the ventilation rate in crops, obtaining the following conclusions:

1) The analysis model can give an overall assessment of a ventilation system if flow can be approximated to obtain a solution.
2) The empirical model has similar abilities to the model of analysis, but develops a database.
3) The small-scale model can be useful to examine the complex problems of ventilation if a similarity of flow can be maintained between the model and reality.
4) The large-scale model is the most reliable in predicting the efficiency of ventilation, but is expensive and time consuming.
5) The multi-zone model is a useful tool for the design of the ventilation of an entire building, but cannot provide detailed flow information in a room.
6) The zone model can be useful when a user has prior knowledge of the flow in a room.
7) The CFD model provides more detailed information on the performance of ventilation and is the most sophisticated. However, the model must be validated by corresponding experimental data and the user must have solid knowledge of fluid mechanics and numerical technique.

Therefore, the choice of an appropriate model depends on the problem to be solved.

Finite element vs. finite volume

In a study by Molina et al. (2010) on the effectiveness of the Finite Element Method (FEM) and Finite Volume Method (FVM) for two-dimensional incompressible turbulent flow in ventilation rates, they found that the MEF requires twice the computation time and 10 times more memory storage than FVM. FVM software (ANSYS/FLUENT v 6.3.) is the most frequently used CFD package in ventilation research, but few papers using FEM software (ANSYS/FLOTRAN v. 11.0) have been published. CFD simulations have been compared to experimental data for 12 cases corresponding to three greenhouse types. The experimental greenhouses were chosen to represent a large range of ventilation situations: Buoyancy effect in a mono-span greenhouse with adiabatic walls, as well as buoyancy and wind effect in a multi-span greenhouse and ventilation.

FUTURE RESEARCH

Advances in telecommunications such as wireless networking and Internet technology (TCP / IP) facilitate the monitoring of environmental conditions in greenhouses. Pontikakos et al. (2005) designed a Web-based application for real-time predictive modelling of temperature and air velocity patterns, which consists of a user interface, interpolation process data generated by CFD and an output interface. A lighting systems model with different optical properties was developed by Mikulka et al. (2010), which shows various settings for the R-FEM method in the CFX environment.

CFD ventilation space still tends to be a slow process today, while the computation time for the ventilation system and control simulation strategy is negligible. Sun and Wang (2010) found that the test method is more effective than the simplified numerical models, which require more powerful computers. Stavrakakis et al. (2010) concluded that artificial neural networks coupled with CFD models are a powerful computational tool to evaluate the energy savings of various architectural designs.

PERSPECTIVE

Many studies focused on defining the conditions for a suitable environment. However, there has been less work on automation and control variables. Investigations that seek greater understanding of the interactions between climate variables are increasing (Figure 1). Studies such as those of Hooff (2010), Teitel (2010) and Fidaros et al. (2010) evaluating geometries have increased in the last year (Figure 2). Most studies show multi-variable relationships, of which temperature and air flow are more common. Humidity has been linked with temperature, while there are still few CO_2 distribution models. Solar radiation is the subject of investigations that evaluate housing, and is also related to the temperature in simulations with a greater degree of realism.

Studies to determine the influence of windward and leeward wind direction (Bournet et al., 2007; Kacira, 2008; Majdoui, 2009; Bournet and Boulard, 2010) (Figure 2) indicated the best aperture settings for optimum environmental conditions inside, but still has unstudied air movement through space of the crop. There have been many studies to determine the geometric design of greenhouses that encourage improvements in weather conditions and the use of new technologies such as monitoring systems in real time, allowing improvements in automation using Web technology (Pontikakos, 2005). Other studies have focused on the evaluation of misting systems (Kim et al., 2007; Gázquez et al., 2008), forced ventilation (Baeza et al., 2008; Hughes and Ghani, 2010) looking for energy savings. Since simulation technology and computing power have improved, accuracy and realism in research has also increased, thereby defining more detailed models and by the use of textures that define the materials of the facilities.

The use of insect-proof screens in commercial greenhouses is very important as a means of crop protection, even when they reduce natural ventilation, which is why there have been many research efforts to reduce its negative influence (Kittas et al., 2005; Harmanto et al., 2006; Majdoubi et al., 2007; Teitel et al., 2008a). These studies tested different designs in size of the box and tilt and determined the most affected areas within the green-house where the use of porous media allowed its CFD simulation. Studies have also investigated the influence of solar radiation on temperature and relative humidity (Tablada et al., 2005; Impron et al., 2007, Tong et al., 2009), and the result in crop response (Baxevanou et al., 2007). Other studies evaluate the incorporation of pigments (Elsner et al., 2008) taking into account the convection and thermal gradients (Figure 3). Most of the studies developed 3D models, some of which reported the use of models of turbulence and buoyancy, which appeared more often in the past two years (Fidaros, 2010; Defraeye, 2010; Majdoubi, 2009). Incorporating turbulence models can make simulations more accurate, in turn increasing the processing and memory requirements for computing resources. Norton and Sun (2006) and Roy and Boulard (2005) expressed the importance of the choice of turbu-lence model that best meets the conditions of the study. Moreover, the concept of buoyancy appears frequently to incorporate the effects of growing space on the air flow and temperature gradients into the models.

In addition, many studies considered growing space, some of which are designed to measure phenomena based on their influence on the development and crop yield (Figure 4). Other studies established and evaluated the influence of crops on the other elements, such as temperature, relative humidity, CO_2 concentration and air flow, where it is necessary to model the space occupied by the crop by using porous media (Fidaros et al., 2010). Other studies also measured biological phenomena such as evapotranspiration and PAR (Baxevanou, 2007; Sun, 2008) using indirect measures of climatic variables. However, some studies do not mention an experimental phase aimed at validating the numerical model. In studies of air flow, the experimental methods most used are scale models and unidirectional anemometry; the tracer gas technique is used less often, as well as three-dimensional anemometry, which is considerably more expensive. Studies that have used new methods to assess ventilation systems, such as those by Lu (2009), Molina (2010), Endalew (2009), van Henten (2008), Mikulka (2010) and Defraeye (2010), have increased in the past three years. The main question is the validation of these studies because they are mainly concerned with real scale greenhouses, whereas the measurements and characterizations have merely been done on scale models (Figure 6).

CONCLUSION

CFD is an area of knowledge that in recent years has developed enormously through the development of software and hardware, which has contributed to research on natural ventilation a greater understanding of the interactions between the variables that make up the climate inside greenhouses. In the past five years, CFD simulation has become increasingly realistic and detailed, obtaining more accurate solutions. However, their use requires extensive knowledge of climatic variables, fluid dynamics and turbulence. Simulating more accurately requires more processing power, so studies tend to use CFD in conjunction with other tools. Further studies are therefore required to incorporate more realistic crops beyond a porous medium, taking into account the role of gas exchange, which is necessary for an understanding of the physiology and phenology of crops. There is still a need to develop high-precision systems in greenhouses, and CFD is a powerful tool for defining parameters with high precision.

ACKNOWLEDGEMENT

This research was partially supported by the Mexican National Council of Science (CONACYT), FIFI 2010 de la Facultad de Ingeniería (UAQ).

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