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# Effect of Temperature on Greenhouse Natural Ventilation under Hot Conditions: Computational Fluid Dynamics Simulations

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**Abstract:** The aim of study was to investigate the effect of temperature on air patterns in two different greenhouse configuration using two-dimensional computational fluid dynamic models. The models were constructed on the basis of two major assumptions: first, the inside temperature is considered to have a vertical distribution while it is constant on horizontal planes; second, temperature is the main driven force that causes air movement. The computational results were validated with current literature data. The models were later used to study the air patterns inside two greenhouse configurations under zero and low wind velocities. The ventilation efficiency was assessed on the basis of the ventilation rate and complemented with the study of the internal air velocities at a height of 1.5 m. Results indicate that applying temperatures as the main driven forces for the buoyancy effect produced a positive correlation and agree with current literature data, therefore, providing a simple way to study the ventilation and inner air patterns. Results also, show that the ventilation in greenhouses due to the temperature effect produces high air exchange rates. However, the study of the inner air patterns reveals that those air patterns occur near the openings causing almost no air exchange in the greenhouse central area due to a stagnant effect that reduces the wind effect throughout the greenhouse.

**Key words:** Air patterns, stagnant effect, air exchange rate, wind effect

## INTRODUCTION

Ventilation is crucial to achieve optimum greenhouse climate. It may be natural or forced ventilation. The first is due to pressure differences caused by wind effect, temperature effect or, most commonly, a combination of both. The latter is achieved mechanically with the use of fans. Natural ventilation is the main method used in most greenhouses to control the indoor climate variables as it is more energy efficient than mechanical ventilation. Achieving a homogeneous climate by natural ventilation, however, is a complex task; it depends on window configuration, greenhouse structure orientation, presence of crops and its row orientation inside the greenhouse. Further, the presence of insect-proof screens in the openings also, causes a reduction in the ventilation rate (Fanatssi *et al*., 2004; Ould Khaoua, 2006; Sase, 2006).

The understanding for natural ventilation in greenhouses still requires more research to improve the design of naturally ventilated greenhouses. Many studies have been carried out using the tracer gas technique (Campen and Bot, 2003; Ould Khaoua, 2006) and energy balance models (Roy *et al*., 2002; Dayan *et al*., 2004). However, these techniques allow for the estimation of the gross ventilation rate without offering further information regarding the internal airflow and the current state of climatic variables within the greenhouse.

As better computers are developed, the use of computational fluid dynamics (CFD) is on the rise in the study of greenhouse ventilation processes. Now many studies have been conducted utilizing either two-dimensional or three-dimensional CFD models taking into account, mainly, the effect of wind on greenhouse ventilation (Mistriotis *et al*., 1997; Fatnassi *et al*., 2003; Campen and Bot, 2003; Rico-Garcia *et al*., 2006; Ould Khaoua *et al*., 2006).

The present research uses a two-dimensional CFD model to study the effect of temperature on natural ventilation considering no-wind and low wind speeds. The objective was to determine the influence of temperature effect on the ventilation process of two different greenhouse configurations currently in use in central Mexico using a commercial package ANSYS-FLOTRAN v11 based on the finite element method (ANSYS, 2007).

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## MATERIALS AND METHODS

**Greenhouse description (Amazcala type greenhouse):** The experimental greenhouse was a multi-span type greenhouse which was located in Queretaro State, Mexico (longitude, 100°16'W; latitude, 20°42'N; altitude, 1920 m). The area covered was 1872 $m^2$ (36 wide and 52 m long). The greenhouse is 6.5 m high with the gutter at 4 m. The ridge was orientated north-south. All the windows were roll-up windows. The roof ventilation area was 250 $m^2$ and the lateral ventilation area was 260 $m^2$; 13.35 and 13.88% of the ground cover area, respectively (Fig. 1a).

**Instrumentation:** Internal air temperatures were read using a LM335 precision temperature sensor (National Semiconductor) whose range of operation is -40 to 100°C with accuracy of ±1°C. It has an output voltage temperature coefficient of ±10 mV°$C^{-1}$ and a thermal response of 4 min for temperature air measurements. All sensors were calibrated in a room kept at a constant temperature of 25°C before they were placed in the measuring positions. At these measuring positions they were protected with a passive solar shield to avoid self heating from the direct solar radiation. The internal temperature measurements were taken on a vertical line at the centre of the greenhouse as indicated in Fig. 1a. This disposition was adopted to know the vertical temperature profile inside the greenhouse.

The external temperature was recorded with a weather station located at a height of 7 m. The measurements of temperatures and all external data were recorded every 5 min. Later, these data were used to determine boundary conditions for the CFD model.

**The data used for the simulations corresponds:** To the summer time, July 22, 2007 at 13:30 h and for the winter time, January 09, 2008 at 2:15 h. Both sets of data were selected on the basis that these represent the hottest time of the day. Two temperature gradients were calculated between the external temperature and the internal temperature at 1.5 m; 17.7°C, for the summer and 3.5°C, for the winter.

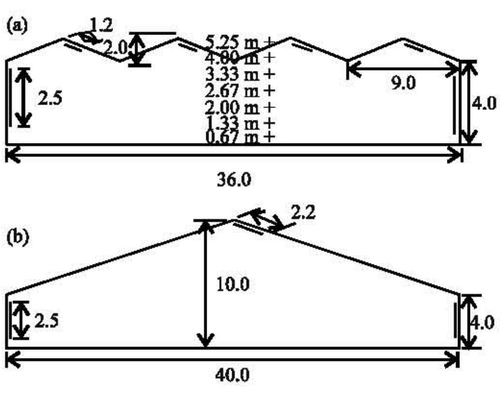



Fig. 1: Greenhouse configurations. All dimensions are in meters. (a) Amazcala greenhouse type. +Temperature measurement position and (b) Zacatecas greenhouse type

**CFD fundamental theory:** The governing equations of a fluid flow and heat transfer can be considered as mathematical formulations of the conservation laws that govern all fluid flow, heat transfer and associated phenomena. These conservation laws describe the rate of change of a desired fluid property as a function of external forces and can be written as:

- **Continuity equation:** Net mass flow out of control volume through its surface, the time rate of decrease of mass inside the control volume:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho u_j\right) = 0 \qquad (1)$$

- **The momentum equation (Newton second law):** The sum of external forces acting on the fluid particle equals its mass times the acceleration of the particle:

$$\frac{\partial}{\partial t}\left(\rho u_i\right) + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = \frac{\partial}{\partial x_j}\left[-p\delta_{ij} + \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \rho g_i \qquad (2)$$

- **The energy equation (the first law of thermodynamics):** The rate of change of energy inside a fluid particle equals the net flux of heat into the particle plus the work done on the particle:

$$\frac{\partial}{\partial t}\left(\rho C_p T\right) + \frac{\partial}{\partial x_j}\left(\rho u_j C_p T\right) - \frac{\partial}{\partial x_j}\left(\lambda \frac{\partial T}{\partial x_j}\right) = s_T \qquad (3)$$

CFD techniques solve the above equations over a discretised flow domain in order to compute the systematic changes in mass, momentum and energy in a flow field. A detail description of the derivation of the equations and applications can be found in Anderson (1995).

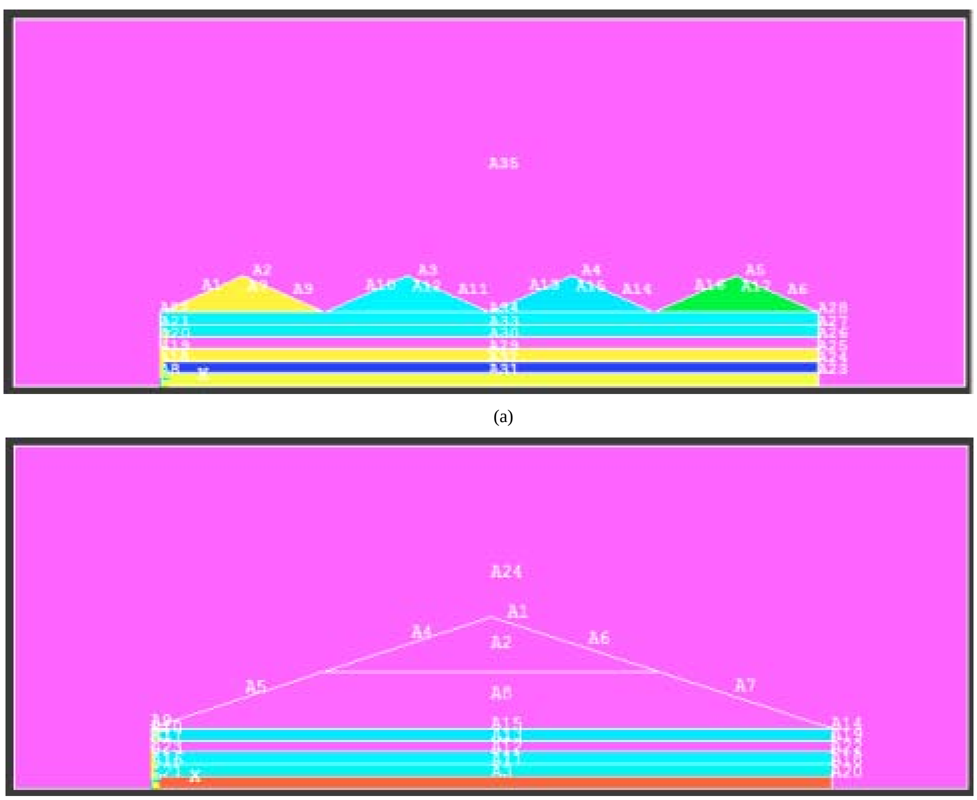
Air flow motion is usually associated with turbulent motion; primarily due to high flow rates and heat transfer interactions involved in the flow field. These turbulent flows are very small (1 mm) compared to that of the scale of the computational grid (Norton *et al.*, 2007). To overcome this problem the use of turbulent models are assumed. The eddy viscosity hypothesis states that an increase in turbulence can be represented by an increase in effective fluid viscosity. The effective fluid viscosity is the sum of the laminar viscosity (which is a property of the fluid) and turbulent viscosity (which is calculated from the turbulence model). The standard k-e (turbulent kinetic energy and dissipation rate) model was adopted for this study, because of its favourable convergence behaviour and reasonable accuracy (Norton *et al*., 2007). It has been successfully used to calculated greenhouse flows (Mistriotis *et al*., 1997; Fatnassi *et al*., 2003; Molina-Aiz *et al*., 2004; Ould Khaoua *et al*., 2006).

The presence of insect-proof screens was taken into account by means of a porous media approach. The flow of air through the porous media can be described by means of the Darcy-Forcheimer equation (Molina-Aiz *et al*., 2004).

$$-\frac{\partial P}{\partial x} = \left(\frac{\mu}{K}\right)u + \rho\left(\frac{Y}{K^{1/2}}\right)|u|u \qquad (4)$$

**CFD model:** The computational domain includes both indoor and outdoor domains; the outdoor domain represents the external air and the indoor domain represents all the parts considered within the greenhouse; plastic covers, insect-proof screens and the internal air. The internal air was divided into seven layers in order to apply in those layers temperatures as loads. The size of the computational domain was proposed in order to allow the flow to be fully developed as follows: for the Amazcala greenhouse model a domain of 52 m long and 20 m high was used, for the Zacatecas greenhouse model a domain of 56 long and 20 m high was used, with the greenhouse at the middle, in both cases (Fig. 2). Plastic covers and insect proof-screens had to be constructed as areas of 1 mm wide as long as the finite element used (FLUID141) cannot be apply to lines. So, all parts in the models have to be taken into account as areas. All the data used to simulate air, plastic films and insect-proof screens are listed in Table 1.

The grid generation was determined by carrying out preliminary simulations to ensure a nondependent grid solution. The size of the finite element to mesh the plastic and insect-proof screen areas resulted in having a geometrical ratio of 1:50; this means that the elements were 1 mm wide and 50 mm long. These areas were meshed with quadrilateral elements in a free way. For the air areas the mesh was denser next to the surface of the



(a) (b)

Fig. 2: CFD models for the configurations studied. (a) Amazcala configuration and (b) Zacatecas configuration

Table 1: Properties values used to simulate air, plastic films and insect-proof screens

| Variables | Model | Values |
|---|---|---|
| **Air** | | |
| Specific heat (J $kg^{-1}$ $K^{-1}$) | | 1004 |
| Thermal conductivity (W//K) | $\lambda = (2.502 E^{-3}T^{3/2})/(T+194.44)$ | |
| $T_o$ = 305 (K) | | 0.0267 |
| $T_o$ = 291 (K) | | 0.0256 |
| Dynamic viscosity (kg $m^{-1}$ $sec^{-1}$) | $\mu = (1.459 E^{-6}T^{3/2})/(T+110.56)$ | |
| $T_o$ = 305 (K) | | $1.870\times10^{-5}$ |
| $T_o$ = 291 (K) | | $1.804\times10^{-5}$ |
| Density (kg $m^{-3}$) | $\rho = P/(287.05T)$ | |
| $T_o$ = 305 (K) | | 0.9296 |
| $T_o$ = 291 (K) | | 0.9743 |
| Atmospheric Pressure (Pa) | (1800 m o.s.l.) | 81388 |
| Gravitational acceleration (m $sec^{-2}$) | | 9.81 |
| **Plastic film** | | |
| Specific heat (J $kg^{-1}$ $K^{-1}$) | | 1800 |
| Thermal conductivity (W/m/K) | | 0.40 |
| Density (kg $m^{-3}$) | | 920 |
| **Insect-proof screens** | | |
| Hydraulic diameter (m) | | $2.7083\times10^{-4}$ |
| Permeability ($m^{-2}$) | | $1.8241\times10^{-8}$ |

Table 2: Summary of the air exchange rates (N, $min^{-1}$). Results for validation

| Configuration | TGT Ould Khaoua *et al.* (2006) | Ould Khaoua *et al.* (2006) | Present methodology | Error 1 (%) | Error 2 (%) |
|---|---|---|---|---|---|
| 2 | 15.9 | 13.1 | 18.7 | 17.61 | 14.97 |
| 3 | 28.3 | 23.7 | 32.4 | 16.25 | 12.65 |

TGT: (Tracer Gas Technique), Error (1): Comparing TGT against Ould Khaoua *et al.* (2006) and Error (2): Comparing TGT against current methodology

walls where, strong gradients are supposed to occur and in order to prevent lose of valuable information. These were meshed with triangular elements in a free way. For the Amazcala greenhouse model 64219 elements were used and for the Zacatecas greenhouse model 18795 elements were used.

**CFD model validation:** The methodology proposed to study the effect of temperature was based on two assumptions. First, the temperature profile, inside the greenhouse, has a vertical variation and is homogeneous on horizontal planes. Second, the temperature inside the greenhouse is supposed to be the driven force to cause the air movement. The latter is only valid when the temperature inside the greenhouse has reached the steady state so that there is an associated air pattern that corresponds to that temperature profile. This approach only permits the study of air exchanges and the distribution of air patterns.

Due to the lack of equipment to measure air exchanges or greenhouse inner wind velocities this approach was validated using the results published by Ould Khaoua *et al.* (2006). It was constructed configurations 2 and 3 and then the two aforementioned assumptions were applied to the models (Table 2).

Once the CFD model was validated the same methodology was used to study the effect of temperature on air motion inside two different configurations: namely, Amazcala greenhouse type-experimental greenhouse (Fig. 1a) and Zacatecas greenhouse type (Fig. 1b). These two configurations were named after the places where, similar configurations are located. The temperature profiles recorded for the Amazcala greenhouse type were applied to both CFD models at seven different layers. Keeping the same temperature profiles, the condition for wind direction was considered in windward and leeward directions and the velocity magnitude was varied from 0.0 (buoyancy) to 2 m $sec^{-1}$ for both configurations. This combination of cases studied amounts to a total of 28 cases for each model (Table 3).

Table 3: Summary of cases analysed

| Layer (m) | | Summer temperatures | | | Winter temperatures | | |
|---|---|---|---|---|---|---|---|
| Amazcala | Zacatecas | T(K) | $T_o$(K) | $\Delta$T(K) | T(K) | $T_o$(K) | $\Delta$T(K) |
| **Temperature distribution on layers** | | | | | | | |
| 0.00-0.67 | 0.00-0.70 | 315.0 | 305 | 17.7 | 294.0 | 291.0 | 3.5 |
| 0.67-1.33 | 0.70-1.40 | 318.9 | | | 294.0 | | |
| 1.33-2.00 | 1.40-2.10 | 322.7 | | | 294.5 | | |
| 2.00-2.67 | 2.10-2.80 | 322.6 | | | 294.5 | | |
| 2.67-3.33 | 2.80-3.50 | 322.5 | | | 295.0 | | |
| 3.33-4.00 | 3.50-6.75 | 323.7 | | | 295.0 | | |
| 4.00-6.00 | 6.75-10.00 | 324.9 | | | 295.5 | | |
| **Wind direction and velocities (m $sec^{-1}$) applied to the models** | | | | | | | |
| Windward | | | | | | | Leeward |
| 0.00 | | | | | | | 0.00 |
| 0.25 | | | | | | | 0.25 |
| 0.50 | | | | | | | 0.50 |
| 0.75 | | | | | | | 0.75 |
| 1.00 | | | | | | | 1.00 |
| 1.50 | | | | | | | 1.50 |
| 2.00 | | | | | | | 2.00 |

T: Temperature applied in each layer; $T_o$: Outside temperature; $\Delta$T: Temperature gradient between $T_o$ and $T_{i(1.5)}$. For each model it was analyzed both temperature gradients and all wind conditions

## RESULTS AND DISCUSSION

**Global ventilation:** These errors are calculated by comparing the total in coming flows and the total out going flows through the openings in both greenhouses. These relative errors are bigger for the temperature gradient of 3.5°C. These differences can be explained by the fact that the velocity measurements made in the CFD models are made along patterns define by hand. Those patterns are defined across the openings of the model so, the flows coming in and out can be computed (Table 4).

Figure 3 corresponds to a temperature gradient of 17.7°C. The temperature effect prevails over the wind effect for wind velocities smaller than 1 m $sec^{-1}$ for both

Table 4: Summary of maximal and minimal errors at computing global ventilation. Error = $[(F_{out} - F_{in})/F_{out}]\times100$

| | Amazcala configuration | | | Zacatecas configuration | | |
|---|---|---|---|---|---|---|
| | Total flow ($m^3$ $sec^{-1}$) | | | Total flow ($m^3$ $sec^{-1}$) | | |
| Velocity (m $sec^{-1}$) | $F_{out}$ | $F_{in}$ | Error (%) | $F_{out}$ | $F_{in}$ | Error (%) |
| **17.7°C temperature gradient** | | | | | | |
| 0.75 L | 2.97 | 2.87 | 3.23 | 2.50 | 2.49 | 0.46 |
| 2.00 L | 4.43 | 4.15 | 6.17 | 4.15 | 403.00 | 2.90 |
| 1.50 W | 3.50 | 3.30 | 5.91 | 3.16 | 3.00 | 5.00 |
| 2.00 W | 4.16 | 4.11 | 1.13 | 3.96 | 3.80 | 4.16 |
| **3.5°C temperature gradient** | | | | | | |
| 0.75 L | 1.46 | 1.43 | 2.12 | 1.43 | 1.38 | 1.38 |
| 1.50 L | 2.94 | 2.60 | 11.61 | 2.71 | 2.62 | 3.33 |
| 0.25 W | 1.37 | 1.29 | 6.40 | 1.21 | 1.10 | 8.81 |
| 0.75 W | 1.38 | 1.38 | 0.16 | 1.37 | 1.34 | 2.18 |

L: Leeward direction; W: Windward direction; $F_{in}$: Flow coming in; $F_{out}$: Flow going out

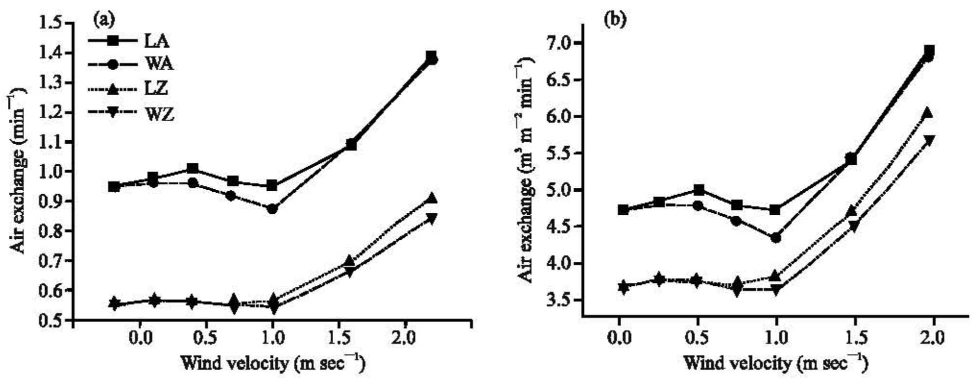



Fig. 3: Calculated ventilation rate for the temperature gradient) of 17.7°C. (a) air exchanges pre min and (b) volume change per unit floor area perunit time. LA = Leeward Amazcala; WA = Windward Amazcala; LZ = Leeward Zacatecas; WZ = Windward Zacatecas

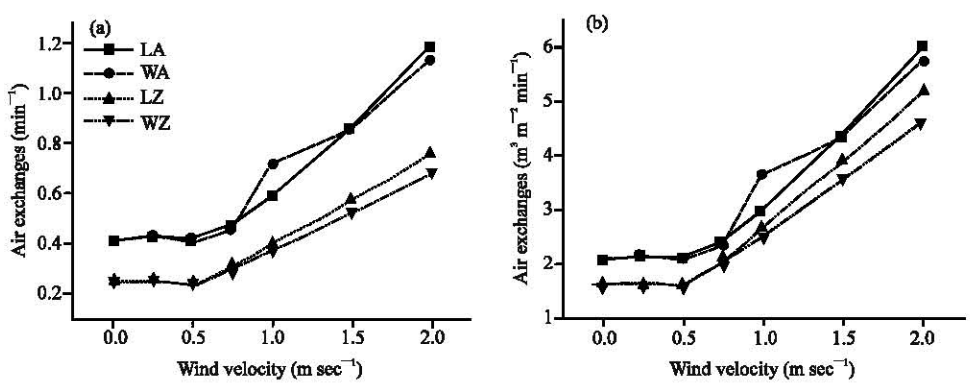



Fig. 4: Calculated ventilation rate for temperature gradient of 3.5°C. (a) air exchanges per min and (b) volume change per unit floor area per unit time. LA = Leeward Amazcala; WA = Windward Amazcala; LZ = Leeward Zacatecas; WZ = Windward Zacatecas

Table 5: Theoretical consideration for free and forced convection

| | | Temperature gradient, 17.7°C $T_i = 322.7$; $T_o = 305$; $\beta = 0.003098$ | | Temperature gradient, 3.5°C $T_i = 291$; $T_o = 294.5$; $\beta = 0.003395$ | |
|---|---|---|---|---|---|
| Velocity (m sec$^{-1}$) | Re | Gr | Gr Re$^{-2}$ | Gr | Gr Re$^{-2}$ |
| $1.0\times10^{-18}$ | $2.50\times10^{-12}$ | $8.41\times10^{12}$ | $1.3\times10^{36}$a | $1.82\times10^{12}$ | $2.9\times10^{12}$a |
| 0.25 | $6.25\times10^{5}$ | $8.41\times10^{12}$ | 21.52a | $1.82\times10^{12}$ | 4.66a |
| 0.50 | $1.25\times10^{6}$ | $8.41\times10^{12}$ | 5.38a | $1.82\times10^{12}$ | 1.16 |
| 0.75 | $1.88\times10^{6}$ | $8.41\times10^{12}$ | 2.39a | $1.82\times10^{12}$ | 0.51b |
| 1.00 | $2.50\times10^{6}$ | $8.41\times10^{12}$ | 1.34 | $1.82\times10^{12}$ | 0.29b |
| 1.50 | $3.75\times10^{6}$ | $8.41\times10^{12}$ | 0.59b | $1.82\times10^{12}$ | 0.13b |
| 2.00 | $5.00\times10^{6}$ | $8.41\times10^{12}$ | 0.33b | $1.82\times10^{12}$ | 0.07b |

a: The wind effect may be neglected; b: The temperature effect may be neglected. No letter means that both effects must be considered, L: Characteristic longitude; 2.5 m. This is the height of lateral openings and $Gr = \frac{g\beta(T_i - T_o)L^3}{v^2}$; Grashof No. $Re = \frac{VL}{v}$; Reynolds No.

configurations, whereas, in Fig. 4, which corresponds to a temperature gradient of 3.5°C, it can be seen how the wind effect prevails over the temperature effect for wind velocities higher than 0.5 m sec$^{-1}$. The temperature effect has an important influence on inner wind velocities from 0.25 to 0.50 m sec$^{-1}$. Though, small differences can be observed the Amazcala type greenhouse has no defined better ventilation rate for windward o leeward wind direction, whereas, for the Zacatecas type greenhouse the leeward ventilation is, in all cases, better than the windward one. These results are in agreement with the theoretical analysis showed in Table 5 where the relation ($Gr/Re^2$) is calculated (Gr: Grashof number and Re: Reynolds number). If ($Gr/Re^2$)≈1 the wind and temperature effect must be consider; if ($Gr/Re^2$)<<1 the temperature effect may be neglected and if ($Gr/Re^2$)>>1 the wind effect may be neglected. When there is no wind velocity this relation tends to infinity ( Incropera and DeWitt, 1996).

In Fig. 3 and 4 it can be seen that the first part of the curves keep almost steady, this stationary behaviour can be explain by the inertial effect caused by temperature. This behaviour is stronger for the 17.7°C temperature gradient. On the other hand, the temperature gradient increases the air exchanges (no wind condition), however, this condition causes air flow patterns near the openings while in the crop region almost no air exchange occur.

The ventilation efficiency can be seen in Fig. 3b and 4b where, the volume change per unit floor area/unit time versus the wind velocity is plotted. The difference in air exchanges/min/area of ventilation between the two greenhouse configurations for the same wind direction is about 1 and 0.5 m$^3$ m$^{-2}$ min$^{-1}$ for the temperature gradients of 17.7 and 3.5°C, respectively. This can be explained if it is observed that the Zacatecas configuration resembles a big chimney (Fig. 2) that promotes the so-called bouyancy effect. These results are similar to those found by Boulard *et al.* (1996) and Mistriotis *et al.* (1997).

**Inner wind velocities:** In Fig. 5 and 6 the inner wind velocities, along a line at 1.5 m high, are plotted. A similar behaviour is found for both greenhouse configurations. However, for external low wind velocities stronger inner wind velocities near the openings, caused by the temperature effect were observed while, at the centre of the greenhouse the inner velocities remained low for the two temperature gradients. In general, it can be observed a larger stagnant effect for the 17.7°C temperature gradient than that for the 3.5°C temperature gradient. In the first case the wind can penetrate about 11 m and in the second case it penetrates 20 m.

**Internal air patterns:** The study of the internal air patterns reveals that the temperature effect produces air movement near the openings while in the low parts in the greenhouse almost no air movement was observed. This condition produces low air exchange in the crop zone (Fig. 7). Consequently, the zone where the crop grows has very small air velocities, especially in the centre of the greenhouse, causing very small air renewal in that zone. This confirms that the ventilation rate is just a parameter that is indicative of the air exchanges per unit time, but it does not offer further information about the air patters inside the greenhouse, this finding agrees with Ould Khaoua *et al.* (2006).

Finally, the validation of the CFD model shows that the methodology applied for this study overestimates the ventilation rate by 15% compared to the results obtained by Ould Khaoua *et al.* (2006). This approach agrees with real data and may be used to study the ventilation process under low wind conditions.

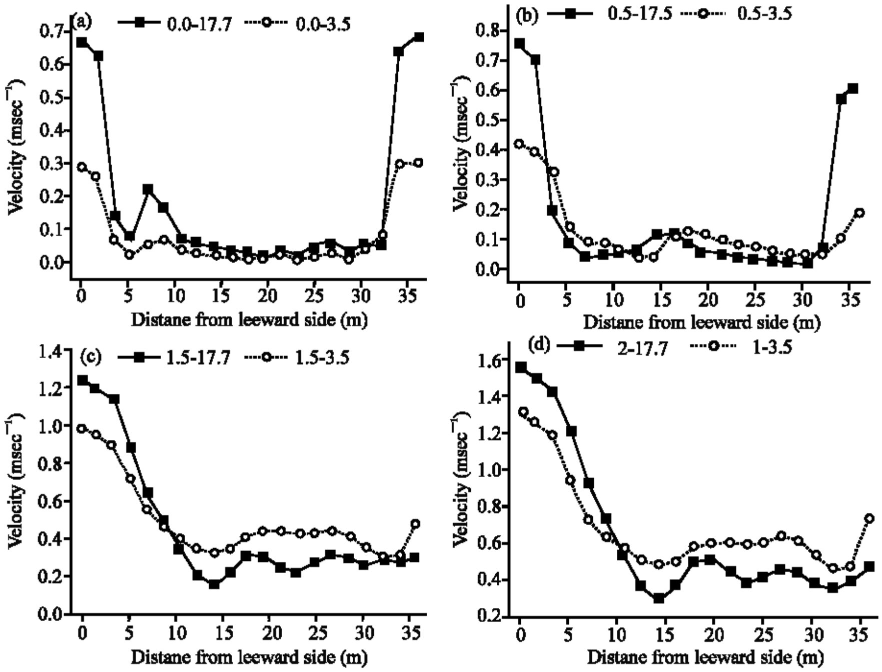



Fig. 5: Velocity magnitude along the cross section for the Amazcala greenhouse type at a height of 1.5 m. For both temperature gradients, ΔT = 17.7°C and ΔT = 3.5°C. (a) Buoyancy condition, (b) 0.5 m sec$^{-1}$ wind velocity, (c) 1.5 m sec$^{-1}$ wind velocity and (d) 2.0 m sec$^{-1}$ wind velocity. 0.0-3.5; the first number indicates wind velocity, the second number indicates temperature gradient

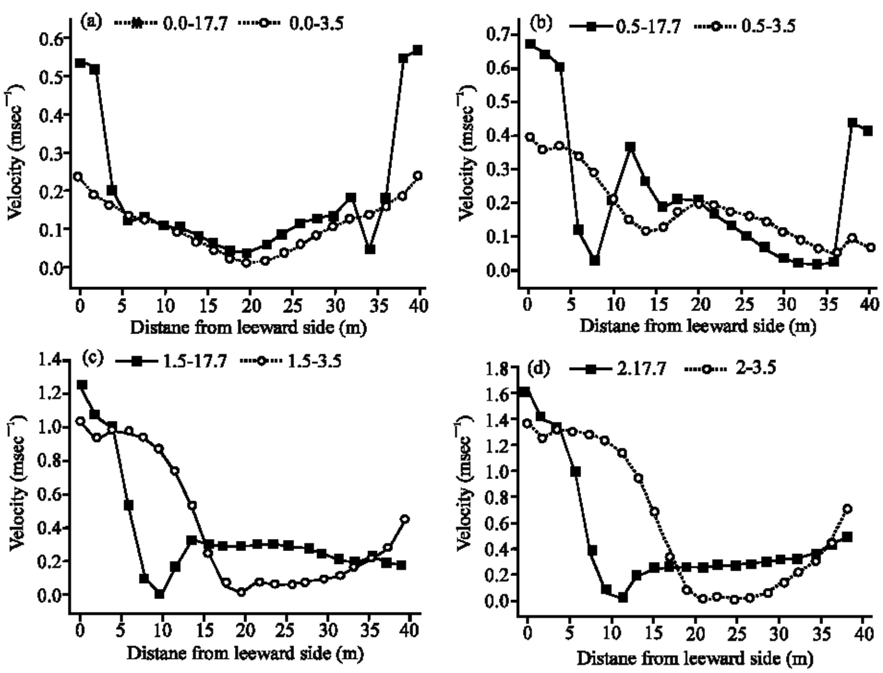



Fig. 6: Velocity magnitude along the cross section for the Zacatecas greenhouse type at a height of 1.5 m. For both temperature gradients, ΔT = 17.7°C and ΔT = 3.5°C (a) Buoyancy condition, (b) 0.5 m sec$^{-1}$ wind velocity, (c) 1.5 m sec$^{-1}$ wind velocity and (d) 2.0 m sec$^{-1}$ wind velocity. 0.0-3.5; the first number indicates wind velocity, the second number indicates temperature gradient

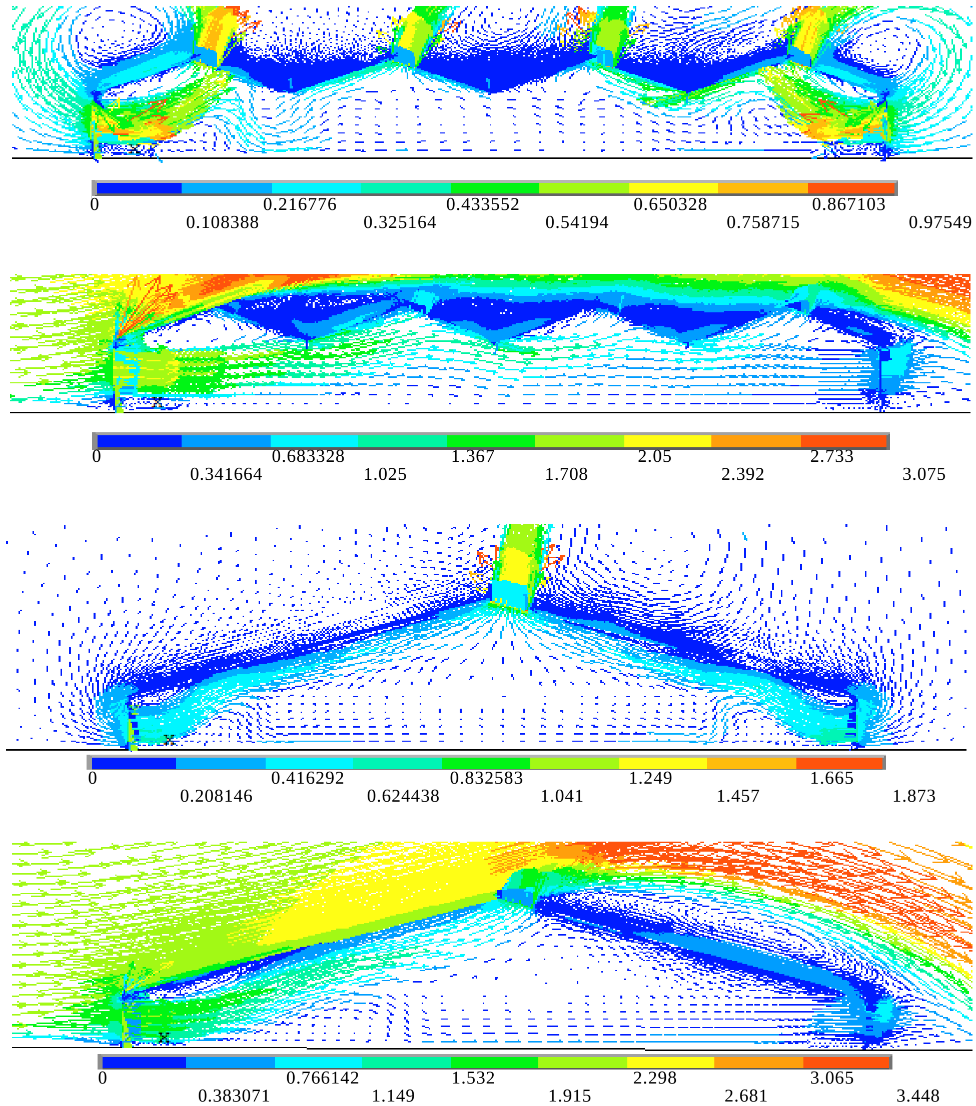



Fig. 7: Computed internal air patterns. 1-17.7; the first number indicates external wind velocity, the second number indicates temperature gradient, (a) Buoyancy-17.7 Amazcala, (b) 2-17.7 Amazcala, (c) Buoyancy-17.7 Zacatecas and (c) 2-17.7 Zacatecas

## CONCLUSION

The temperature effect in hot climates produces high ventilation rates. This condition could represent an advantage for hot climates. Though gross ventilation rates may be deceptive as long as the main air patterns occur near the openings whereas in the zone where the crop grows very small air exchanges occur. It was shown that the temperature effect produces a stagnant effect. The bigger the temperature gradient, the bigger the stagnant effect is.

## ACKNOWLEDGMENTS

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**Notation:**

$C_p$ = Specific heat capacity (J $kg^{-1}$ $K^{-1}$)
g = Acceleration of gravity (m $sec^{-2}$)

K = Porous media permeability ($m^2$)
N = Air exchange per minute ($min^{-1}$)
P = Pressure (Pa)
$s_T$ = Thermal sink or source ($W\ m^{-3}$)
T = Temperature (K)
$T_i$ = Inside air temperature (K)
$T_o$ = Outside air temperature (K)
u = Velocity component ($m\ sec^{-1}$)
V = Velocity magnitude ($m\ sec^{-1}$)
Y = Inertial factor of screen (non dimensional)
x = Cartesian coordinates (m)
$\Delta T$ = Temperature gradient (K)
$\beta$ = Coefficient of thermal expansion ($K^{-1}$)
$\rho$ = Fluid density ($kg\ m^{-3}$)
$\mu$ = Dynamic viscosity ($kg\ m^{-1}\ sec^{-1}$)
$\lambda$ = Thermal conductivity ($W\ m^{-1}\ K^{-1}$)
$\nu$ = Cinematic viscosity ($m^2\ sec^{-1}$)

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