Optimization of ventilation and its effect on the microclimate of a colombian multispan greenhouse

Optimización de la ventilación y su efecto en el microclima de un invernadero multitúnel colombiano

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ABSTRACT

In Colombia, greenhouse design optimization has not been a relevant topic and, as a consequence, the ventilation systems of current structures are not optimal, generating inadequate microclimates for the development of horticultural species. At the production level, management of the greenhouse climate is deficient, and this factor is not taken into account as a function of characteristics dependent on greenhouse design that cannot be modified during its lifespan. The aim of the present work was to study the efficiency of modifications applied to the ventilation system of a commercial greenhouse available on the Colombian market. This was accomplished by using numerical simulations through the application of the computational fluid dynamics method. Based on the commercial greenhouse design, two modified models were designed by applying structural modifications and changing the orientation of the fixed open ridges. Simulations with the three greenhouse models were carried out in order to maximize the air renovation rates and improve air movement within the entire greenhouse, striving for the highest degree of climate homogenization. The best greenhouse design was the one with the highest air renovation index, high enough to ensure adequate control of temperature and humidity extremes through natural ventilation. Additionally, this design generated the most homogenous microclimate within the cultivation zone

Key words: fluid dynamics, greenhouse crops, optimization methods, simulation.

RESUMEN

En Colombia la optimización del diseño de los invernaderos no ha tenido mayor relevancia y en consecuencia las estructuras existentes presentan deficiencias en su ventilación, generando así microclimas inadecuados para los cultivos. A nivel productivo, el manejo climático es deficiente, olvidando que el microclima interior es función de características de diseño del invernadero. El objetivo del trabajo fue el de estudiar la eficiencia de variantes introducidas a la ventilación de un invernadero multi-túnel mediante simulaciones numéricas empleando el método de dinámica de fluidos computacional. A partir del modelo comercial se diseñaron dos variantes experimentales realizando cambios estructurales y de orientación de las ventanas cenitales fijas. Los tres diseños de invernaderos fueron sometidos a simulaciones por computador con el propósito de maximizar los índices de renovación de aire, mejorar el movimiento del flujo de aire en toda la estructura y buscar una homogeneidad en el microclima. El diseño más adecuado fue aquel que presentó un índice de renovación de aire suficiente para garantizar un adecuado control de la temperatura y la humedad a través de la ventilación natural. Este diseño generó además el microclima más homogéneo dentro de la zona de cultivo.

Palabras clave: dinámica de fluidos, cultivos de invernadero, métodos de optimización, simulación.

Introduction

Greenhouses are closed environments, inside which temperature increases due to a cover that holds radiation and also reduces airflow into the structure (Gil *et al.*, 2011). The use of greenhouses in agriculture has been restricted almost entirely to the production of horticultural species. However, in Colombia, the largest share of greenhouses is used for the production of ornamental species, while, in the case of vegetables, it is limited almost exclusively to the production of the tomato. In Colombia, the predominant greenhouse climate control is carried out with natural ventilation. This is a passive method that depends on two forces to generate air movement; forced convection caused by the outside wind and free convection caused by the temperature difference between the outside and the inside of the greenhouse (Boulard *et al.*, 1996).

Natural ventilation is a process that directly influences the climate inside the greenhouse (Bailey, 1995; Kittas *et al.*,

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1996; Mistriotis *et al*., 1997) and is a decisive factor when it comes to designing. A properly designed ventilation system can improve climate control and, consequently, optimize energy use (De Jong and Bot, 1992; ASHRAE, 1993). In addition, ventilation is related to other factors such as temperature, humidity and CO_2 concentration, which directly influence the growth and development of crops (Bot, 1983; Castilla, 1994; Kittas *et al*., 1997).

Ventilation affects the temperature inside the greenhouse; during times of high solar radiation, it is necessary to circulate air from the outside to the inside of the greenhouse in a homogeneous manner in order to remove excess heat. Inadequate ventilation generates overheating and excessive transpiration, leading to problems such as plant water stress and physiological disorders, including fruit cracking and abortion of flowers and fruits. On the other hand, natural ventilation helps evacuate excess moisture and prevent its accumulation in the air layer near the leaves which can cause condensation, leading to the onset of diseases (Gil *et al*., 2011). Poor ventilation has a negative impact on indoor air composition, mainly by reducing the CO_2 concentration (Hand, 1984; Lorenzo *et al*., 1990; Lorenzo, 1994). This is because outside air intake is the main source of CO_2 in greenhouse crops that do not have a source of carbon enrichment, such as in Colombian structures. The efficiency of natural ventilation depends on factors such as wind speed and direction, temperature differences between the outside and the inside of the greenhouse, greenhouse design and the presence or absence of crops (Ould-Khaoua *et al*., 2006).

Computational fluid dynamics (CFD) have been used in recent decades as a tool for modeling greenhouse climate (Reichrath and Davies, 2002; Bartzanas *et al*., 2002). CFD is a method that studies the behavior of fluids, gases or liquids, and their interaction with the environment around them. Most studies have focused on the study of natural ventilation with two basic purposes: from the physical point of view, to describe the movement of airflow and temperature distribution inside the greenhouse; and from the structural point of view, to optimize the size and position of ventilation windows.

CFD-based studies were developed from the early work of Okushima *et al.* (1989). In recent years, CFD has been used as the primary tool to analyze ventilation systems in agricultural buildings, as reviewed by Norton *et al*. (2007). CFD modeling applied to greenhouse design and efficiency has achieved great recognition around the world. This has allowed detailed studies such as the assessment of the effect of installing anti-insect screens in greenhouses (Fatnassi *et al*., 2006). Simple models of CFD that consider air movement into an empty greenhouse under isothermal conditions has been used the most (Kittas *et al*., 1997; Boulard *et al*., 1996; Reichrath and Davies, 2002; Bartzanas *et al*., 2004; Molina-Aiz *et al*., 2004).

Molina-Aiz *et al*. (2004) performed an analysis of the natural ventilation of an Almería-type greenhouse under two conditions (with and without crop) using CFD. When the crop is present, the heat and vapor exchanges between the crop and air must be included. These authors determined that roof windows are of great importance to the efficient ventilation of these greenhouses. Ortiz (2004) conducted the numerical simulation of the natural ventilation of a ten-span Colombian greenhouse. This study reported a decrease in the airflow rate as it flowed along the geometry of the greenhouse, due to frictional forces.

Rico-Garcia *et al*. (2006) studied the effect of wind on the ventilation of two greenhouse configurations using two-dimensional simulations and field measurements to validate these simulations. This study found that larger roof ventilation areas generate better renewal rates for different wind directions. Ould-Khaoua *et al*. (2006) used a two-dimensional CFD model to study the effect of wind speed and window configuration on the ventilation and temperature patterns inside a greenhouse. The authors concluded that maximizing the air exchange rate does not always lead to better climate conditions inside the greenhouse, especially at the plant level. Baeza *et al*. (2007) compared, through CFD simulations, the air exchange and influx of greenhouses with slopes between 12 and 32°C. They concluded that ventilation improved as the slope of the roof increased to 25°C, while for larger slopes, the increase in ventilation was minimal.

In Colombia, the optimization of greenhouse design has been limited and today continues to use the traditional structure established over 30 years ago (Bojacá *et al*., 2011). To begin to address such shortcomings, the objective of this study was to optimize the design of a multispan greenhouse available on the Colombian market through maximizing the air exchange rates and improving the microclimate within the greenhouse.

Materials and methods

Greenhouse prototype

The initial greenhouse design corresponded to a commercial model offered on the Colombian market. The configuration of the prototype consisted of a multispan polyethylene greenhouse of four spans with a total area of 1,920 m^2. The dimensions of each span were 8 m wide × 60 m long, and the greenhouse was oriented north-south on its longitudinal axis.

The greenhouse had vents on each lateral wall and fixed roof ventilation on all four spans. The roof ventilation windows were complemented with two rollable ridge windows in the middle of the greenhouse. From this prototype, we designed two additional greenhouse models; including changes to the orientation of the fixed roof openings and the radius of the roof curvature. The description of the designs and a diagram are presented in Tab. 1.

Numerical simulation

The Navier-Stokes equations are a set of mathematical expressions that define the dynamic behavior of a fluid, derived from the application of the principles of conservation of mechanical energy and thermodynamics to the case of fluids, where the integral formulation is usually transformed to its differential form to be more practical. The set of equations for the two-dimensional steady-state flow without compression is as follows:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad \text{Eq. (1)}$$

$$\rho \frac{\partial}{\partial x_j}(u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i \quad \text{Eq. (2)}$$

$$\rho \frac{\partial}{\partial x_i}(u_i h) = \frac{\partial}{\partial x_i}\left(k \frac{\partial T}{\partial x_i}\right) + \frac{\partial P}{\partial T} + u_i \frac{\partial P}{\partial x_i} + \tau_{ij} \frac{\partial u_i}{\partial x_i} \quad \text{Eq. (3)}$$

where u_i is the speed component in direction i (m s^{-1}), x_i represents direction i, ρ is the air density (kg m^{-3}), P represents the air pressure (Pa), g_i is the gravity acceleration (m s^{-2}), h represents the enthalpy (J kg^{-1}), k is the coefficient of thermal conductivity for the air (W m $°K^{-1}$), T is the absolute air temperature (°K), and μ represents the air molecular viscosity (kg m^{-1} s^{-1}).

Numerical arrangement

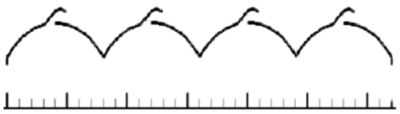
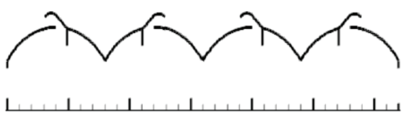
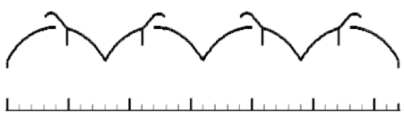
Optimization of the greenhouse prototype was done in two dimensions by creating a model to represent a cross-section of the structure. This cross section was included within a large computational domain (50 m height × 132 m length) using ICEM CFD v.11.0 software (Ansys Fluent Inc.). The computational domain consisted of an unstructured mesh divided into 30,1344 cells. The quality of the grid was evaluated, as this is a fundamental criterion for establishing the accuracy of the solutions obtained by CFD. The quality parameters evaluated were mesh cell size and its variation, finding that 99.5% of the grid cells were in ranges of high quality (0.95 to 1.00).

The Fluent v. 6.3 software (Ansys Fluent Inc.) was used to solve Eqs 1-3, using the finite volume method. Convergence criterion for every time step was set to 10^{-6} for the continuity, momentum and *k*-epsilon transport equations. The standard *k*-epsilon model (Launder and Spalding, 1974) was selected to represent the turbulence model because it has been proven to give satisfactory agreement in greenhouse ventilation flow studies (Bartzanas *et al*., 2004; Fatnassi *et al*., 2006). All simulations considered the energy equation to study the effects of ventilation in the scalar field of temperature inside the greenhouse. Similarly, the fluid properties were fixed to the Boussinesq approximation, which allowed modeling of the air buoyancy effect due to air density variation.

Boundary conditions

The air entered the computational domain through the left side with a uniform wind speed profile of 1 m s^{-1} (Baeza, 2007), while the right side was set as the air outlet. The upper side of the computational domain was defined by a series of symmetric properties to prevent friction losses in the airflow contacting this surface. The simulations considered the atmospheric characteristics of the Sabana

TABLE 1. Description of the greenhouse models evaluated through CFD.

Model	Description	Diagram
M1	Greenhouse with a height of 3 m under the gutter and 5 m under the ridgepole. Presence of a fixed roof window of 0.7 m in the four spans, oriented in the same direction. Presence of rollable windows on the roof for spans 2 and 3, with an opening of 2.7 m each	
M2	Greenhouse with a height of 3 m under the gutter and 5 m under the ridgepole. Presence of a fixed roof window of 0.7 m in the four spans, with alternate orientation. Presence of rollable windows on the roof for spans 2 and 3, with an opening of 2.7 m each. Presence of a 1 m vertical barrier on the ridge of each span	
M3	Greenhouse with a height of 3.5 m under the gutter and 5 m under the ridgepole. Presence of a fixed roof window of 0.7 m in the four spans, with alternate orientation. Presence of rollable windows on the roof for spans 2 and 3, with an opening of 2.7 m each. Presence of a 1 m vertical barrier on the ridge of each span	

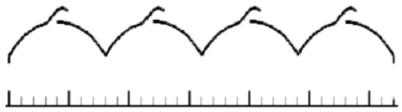
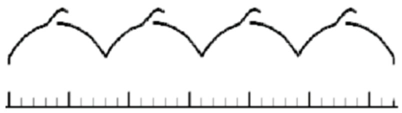
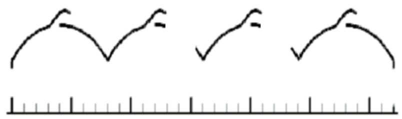
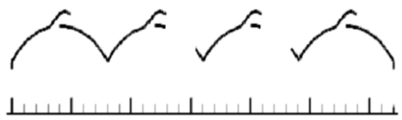
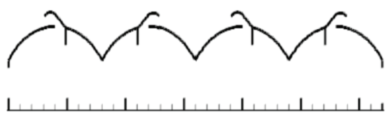
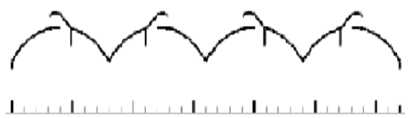
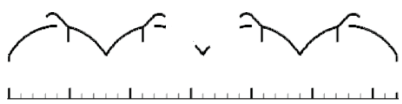
de Bogota such as pressure of 74,980 Pa and gravitational acceleration of 9.81 m s^{-1}. Other parameters considered for the boundary conditions were the viscosity of the air ($1.7 \cdot 10^{-05}$ kg m^{-1} s^{-1}), outside air temperature (20°C), indoor temperature (24°C), greenhouse soil temperature (28°C) and outside soil temperature (23°C). The bottom of the domain (i.e. the soil) and the greenhouse structure were considered as walls, taking into account their physical and thermal properties (Tab. 2).

Eight simulations were performed, using the greenhouse prototype and its variants, considering the same boundary conditions. For some cases, the wind direction changed, as shown in Tab. 3. The simulations considered varying degrees of opening for the different ventilation configurations. The results of the simulations in terms of wind speed and temperature distribution patterns within each greenhouse were used to establish the most optimal greenhouse design.

TABLE 2. Physical and thermal properties of the materials included in the computational domain established to evaluate each of the greenhouse models and ventilation configurations.

Material	Density (ρ, kg m^{-3})	Conductivity (k, W m^{-1} K^{-1})	Specific heat (Cp, J kg^{-1} K^{-1})
Soil	1.300	1.0	800
Polyethylene	923	0.38	2300
Air	1.225	0.0242	1006.43

TABLE 3. Description of the CFD simulations considering variations in the configuration of the vents (VL: lateral ventilation, VCF: fixed roof ventilation, VCE: rollable roof ventilation), opening degree (0%: closed ventilation, 100% fully opened ventilation) and wind direction.

Simulation	Description	Wind direction	Diagram
M1S1	VL: 100%, VCF: 100%; VCE: 0%	⇨	
M1S2	VL: 100%, VCF: 100%; VCE: 0%	⇦	
M1S3	VL: 100%, VCF: 100%; VCE: 100%	⇨	
M1S4	VL: 100%, VCF: 100%; VCE: 100%	⇦	
M2S1	VL: 100%, VCF: 100%; VCE: 0%	⇨	
M2S2	VL: 100%, VCF: 100%; VCE: 100%	⇨	
M3S1	VL: 100%, VCF: 100%; VCE: 0%	⇨	
M3S2	VL: 100%, VCF: 100%; VCE: 100%	⇨	

Results and discussion

The simulation results indicated that there are large airflow differences due to the configuration of the open vents. In general, all the cases considered showed that after air enters the greenhouse, velocity decreases, starting with the first span (Fig. 1). These results agree with those from Mistriotis *et al*. (1997), who stated that in multispan greenhouses with several openings, airflow has greater heterogeneity. This complexity is reflected in the airflow gradient created inside the greenhouse, which largely determines other climate variables such as temperature.

Fig. 1 shows the calculated contours of wind speed and temperature distribution for the M1S1 simulation. This simulation represents the predominant configuration of ventilation in Colombian greenhouses and, through the simulation carried out using CFD, it was noted that this model is the one with the poorest air circulation compared to the other simulated cases. Wind speeds in the whole profile of the emissions were low, especially in the area of the roof where the airflow rates were almost nil.

a) Wind Speed

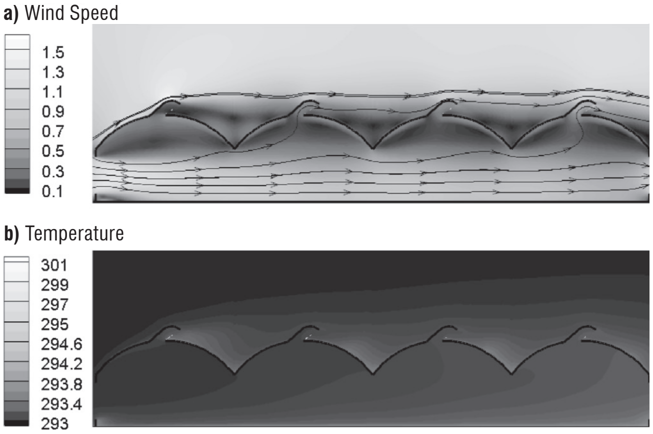


FIGURE 1. Simulated contours for (a) wind speed (m s^{-1}) and (b) temperature distribution (° K) for the M1S1 simulation.

TABLE 4. Air renewal rates and average temperature (± standard deviation) of each of the greenhouse models and configurations simulated by CFD.

Case	Renewal index (volumes h^{-1})	Temperature (°K)
M1S1	33.6	293.9 ± 1.30
M1S2	33.8	293.8 ± 1.10
M1S3	38.7	293.8 ± 1.31
M1S4	48.7	293.8 ± 1.11
M2S1	45.2	293.5 ± 0.36
M2S2	58.1	293.6 ± 0.35
M3S1	49.9	293.3 ± 0.27
M3S2	66.6	293.4 ± 0.29

For abbreviations see Tab. 3.

Consequently, the air turnover rate was the lowest of all the cases considered (Tab. 4). This renewal value is below the recommendation for a naturally ventilated greenhouse, where higher rates are recommended to the 40 volumes (Montero, 2006; ASAE, 1991).

The M1S1 simulation presented a very marked variation in temperature along the greenhouse profile, generating a heterogeneous internal microclimate. Such situations are not recommended for growth and development of crops and can even cause heterogeneous production, both in quantity and quality (Bojacá *et al*., 2009). Similarly, the generation of these patches may favor the development of problems associated with pests and diseases.

The M1S2 simulation changed the input direction of the wind, placing the fixed ridge windows into the wind. The simulation results indicated that the exchange rate times did not increase significantly (0.71%) compared to the M1S1 simulation. However, increased air intake area generated a loss of speed in the side windows as a result of the turbulence generated by the air entering through the fixed ridge windows. This simulation confirms the disadvantages of the current greenhouse design by making the inside temperatures too heterogeneous.

In the cases of the M1S3 and M1S4 simulations, the ventilation area increased by opening the rollable roof windows completely. This new vent configuration had a direct impact on the greenhouse microclimate, generating an increase in air exchange rates (Tab. 4). Although the range was narrower, temperature inside the greenhouse did not fully homogenize the internal microclimate at the height of the growing area, mainly because the airflow moves across the top of the greenhouse without interacting with the lower areas where the crop develops.

The following simulations considered a greenhouse with open fixed ridge windows oriented in an alternated way, while adding a vertical barrier on the roof. The purpose of this barrier is to guide the airflow into the growing area. Previous studies have shown that the air entering through the open fixed ventilation of the first span moves throughout the top of the greenhouse without mixing with the air of the cultivated area and exits through the second span (Nielsen *et al*., 2002).

Fig. 2 shows the wind speed and temperature distribution for the M2S1 simulation. In this case, it is observed how changes in the configuration of vents make each pair of successive windows act as an input and output of the airflow.

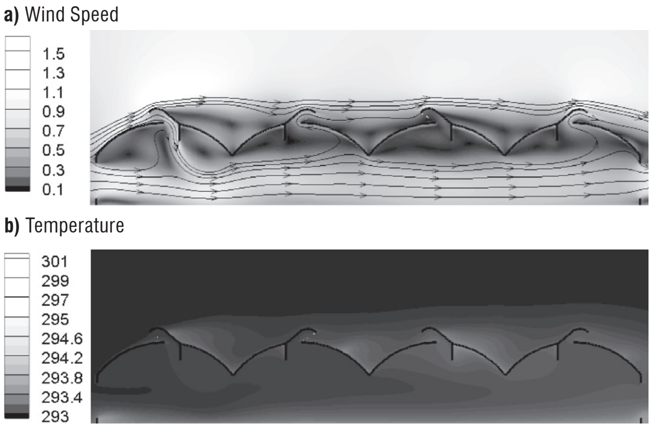


FIGURE 2. Simulated contours for (a) wind speed (m s^{-1}) and (b) temperature distribution (° K) for the M2S1 simulation.

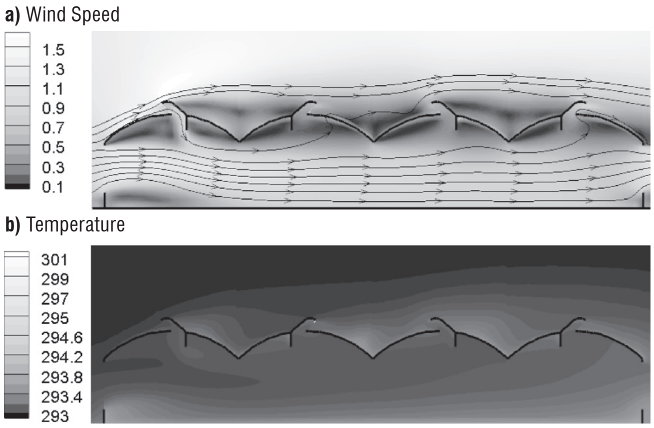


FIGURE 3. Simulated contours for (a) wind speed (m s^{-1}) and (b) temperature distribution (° K) for the M3S1 simulation.

Consequently, there was an increase in the air exchange rate of 34.6% compared to the M1S1 simulation. The results indicated a greater uniformity of temperature inside the greenhouse, mainly in the crop area. However, problems still exist with the movement of airflow near the cover area, registering low air speeds in some sectors. Such situations continue to be unfavorable because the accumulation of moisture in this area causes condensation dripping on the plants, favoring the emergence of diseases.

For this design but with the rollable windows fully opened (M2S2), the problem persisted despite the consequent increase in the air exchange rate. The third greenhouse model (M3) was based on the M2 model but with a higher radius of roof curvature (less concave), generated by increasing the minimum height under the gutter by 0.5 m. The simulation results for this greenhouse (M3S1), represented in Fig. 3, show how these changes positively impacted airflow movement, increasing the air renewal rate. This resulted in a more uniform climate inside the greenhouse at the crop level area. The M3S2 simulation (Fig. 4), with the rollable windows fully opened, had the highest air exchange rate of all the cases considered. These results indicate that the excesses of temperature and humidity can be controlled by natural ventilation with a suitable window configuration.

Simulation results showed that the removal or closure of one of the rollable sidewall vents dramatically decreases ventilation inside the greenhouse. Additionally, in several simulations, it was clear that, even with continuous ridge vents, the airflow is very low if the greenhouse does not have sidewall vents. This demonstrates that more ventilation is achieved through lateral ventilation; therefore, it is important that the greenhouses have these types of vents. However, it is not just the presence of sidewall vents that matters but also ensuring their functionality by avoiding the presence of nearby barriers such as trees or other structures that may affect the airflow input. The presence of an impermeable barrier (e.g. trees or other greenhouses) can block airflow and, as a consequence, ventilation inside the greenhouse is drastically reduced (Mistriotis and Braissoulis, 2008). For this reason, it is not only necessary to improve the design of greenhouses but also to keep greenhouse surroundings clear to promote airflow.

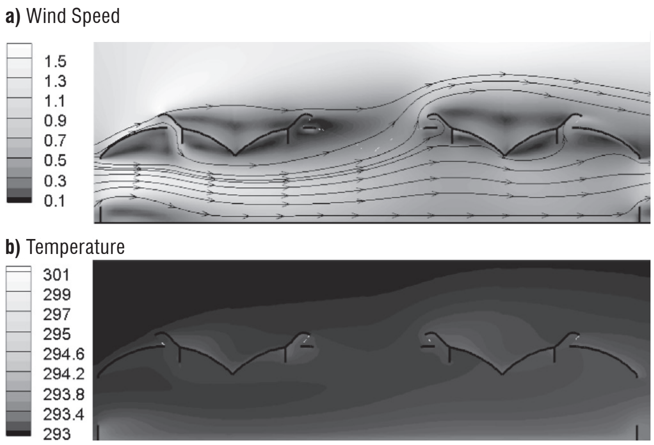


FIGURE 4. Simulated contours for (a) wind speed (m s^{-1}) and (b) temperature distribution (° K) for the M3S2 simulation.

Conclusions

CFD simulations represent a useful design tool to improve ventilation in greenhouses. This methodology allows improvements to be made and evaluated for both existing structures and those marked for installation, saving time and money. Computer simulation as a design tool replaces the actual construction of prototypes, allowing faster progress in the optimization process of naturally ventilated Colombian greenhouses.

The improvements to the structure (increasing the radius of roof curvature, installation of vertical barriers on the roof) combined with the study of different ventilation settings (fixed ridge ventilation orientation in combination with side windows) maximized the natural ventilation of a multi-span Colombian greenhouse by 98%. The ability to maintain homogeneous weather conditions inside a greenhouse, as much as possible, largely depends on the structural design and the configuration of the ventilation system.

Acknowledgements

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