

## SCIENTIFIC ARTICLE

# Study of natural ventilation in a Gothic multi-tunnel greenhouse designed to produce rose (*Rosa spp.*) in the high-Andean tropic

Edwin Andres Villagran Munar<sup>1\*</sup>, Carlos Ricardo Bojacá Aldana<sup>2</sup>**Abstract**

In tropical regions the production of ornamentals is developed exclusively in naturally ventilated plastic greenhouses, which sometimes leads to inappropriate microclimates with high temperatures and humidity that limit the productive development of plants. The aim of this work was to study air flows, temperature distribution and relative humidity inside an alternative greenhouse designed to produce rose (*Rosa spp.*). Three configurations of ventilation, side ventilation (SV), roof ventilation (RC) and combined roof and side ventilation (RSV) were analyzed. The methodological development was based on the use of a previously validated CFD-2D numerical simulation model, which showed an adequate fit between the measured and simulated data, obtaining MAE and RMSE values for temperature and relative humidity of 0.44 and 0.47 °C, 3.99% and 4.04% respectively. The results obtained for the predominant climatic conditions of the study region showed that the highest ventilation rates were obtained for RSV, with values of 0.044 and 0.182 m<sup>3</sup>m<sup>-2</sup>s<sup>-1</sup>, this ventilation efficiency propitiated the generation of a homogeneous microclimate, with temperature and relative humidity values adequate to produce rose (*Rosa spp.*).

**Keywords:** Microclimate, ventilation rate, CFD simulation, temperature, relative humidity, finite volumes.

**Resumo****Estudo da ventilação natural em uma estufa gótica multi-túnel projetada para produzir rosa (*Rosa spp.*) no trópico alto-andino.**

Nas regiões tropicais, a produção de plantas ornamentais é desenvolvida exclusivamente em estufas plásticas ventiladas de forma natural, o que significa que em algumas ocasiões microclimas inadequados são gerados com altas temperaturas e umidade que limitam o desenvolvimento produtivo das plantas. O objetivo deste trabalho foi estudar os fluxos de ar, a distribuição de temperatura e umidade relativa do ar dentro de uma estufa alternativa projetada para a produção de rosa (*Rosa spp.*). Três configurações de ventilação, ventilação lateral (SV), ventilação de telhado (RC) e telhado combinado e ventilação lateral (RSV) foram analisadas. O desenvolvimento metodológico baseou-se na utilização de um modelo de simulação numérica CFD-2D previamente validado, que mostrou um ajuste adequado entre os dados medidos e simulados, obtenção de valores de MAE e RMSE para temperatura e umidade relativa de 0,44 e 0,47 ° C, 3,99 e 4,04% respectivamente. Os resultados obtidos para as condições climáticas predominantes da região de estudo mostraram que as maiores taxas de ventilação foram obtidas para o RSV, com valores de 0,044 e 0,182 m<sup>3</sup>m<sup>-2</sup>s<sup>-1</sup>, essa eficiência de ventilação propiciou a geração de um microclima homogêneo, com valores de temperatura e umidade relativa adequados para a produção de rosa (*Rosa spp.*).

**Palavras-chave:** Microclima, taxa de ventilação, simulação de CFD, temperatura, umidade relativa, volumes finitos.

**Introduction**

Although there are currently high-tech commercial greenhouses that allow total control of climate variables that affect agricultural production, through active climate control strategies, their use and implementation is limited to some countries mainly in northern Europe. Colombia is the second largest exporter of cut flowers after Netherlands (Arévalo et al., 2014), where roses are one of the main export products due to their high commercial demand in international markets for their beauty, fragrance and long-

lasting floral qualities (Getachew et al., 2012). This crop faces a series of production limitations due to phytosanitary problems such as downy mildew and grey mold, caused by *Chromista Peronospora sparsa* and *Botrytis cinerea* respectively, that in tropical and subtropical countries they have the capacity to generate devastating damage to plants (Bautista Silva et al., 2016). The control strategy for these diseases has been based on the indiscriminate use of systemic fungicides, which generates an important economic and environmental cost for the control efficiency obtained, since the development of these diseases occurs under con-

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ditions of high humidity (Debener and Byrne, 2014), which could be limited with the use of suitable greenhouses for production.

In Colombia the rose is produced in productive systems under passive greenhouses, where the climate control strategy is based exclusively on the use of the natural ventilation phenomenon, which being a simple and efficient method of climate control is economically viable (Lee et al., 2018). Natural ventilation is still widely used in greenhouses in countries such as Spain, China, Mexico and Colombia (McCartney and Lefsrud, 2018). This phenomenon depends on two driving forces: forced convection or dynamic ventilation caused by the action of the outside wind and free convection or thermal ventilation caused by buoyancy due to temperature differences between the outside and inside of the greenhouse (Espinoza et al., 2017). Ventilation affects the indoor temperature of the greenhouse in such a way that at times of high radiation it is necessary to circulate air from the outside to the inside of the greenhouse in a homogeneous way to control temperature excesses. This movement of air flow must also allow the exchange of mass and heat between the crop plants and the air circulating in the greenhouse (He et al., 2017). Natural ventilation controls excess moisture and maintains CO<sub>2</sub> levels in ranges close to the level present in the atmosphere, which does not limit the photosynthesis process in plants (Molina-Aiz et al., 2017).

Computational fluid dynamics (CFD) is a robust tool for predicting and studying the natural ventilation phenomenon in greenhouses and its influence on the generated microclimate (Tong et al., 2018). This numerical simulation tool allows the development of 2D and 3D studies, where different study variables or environmental scenarios can be incorporated for evaluation, with the great methodological advantage of carrying out the different experiments without the need to build prototypes or real scenarios (Bouhoun Ali et al., 2017), obtaining results that have proven to be

reliable (He et al., 2017). The use of CFD for the study of natural ventilation in different types of greenhouses has been extensive and significant as summarized in the work developed by (Bournet and Boulard, 2010) and currently the two-dimensional approaches continue to prove to be a simplification that generates precise results in research focused on the study of the configuration of ventilation in greenhouses and its effect on the microclimate (Benni et al., 2016).

This research used an experimental approach that contemplated the implementation and validation of a CFD-2D model, used to simulate the behavior of airflow and its incidence on temperature and relative humidity distributions within an alternative greenhouse model designed for rose production under the prevailing climatic conditions in a region of the Bogota savannah. The aim of this study was to quantify and analyze ventilation rates and their influence on the microclimate generated inside the greenhouse under three specific ventilation configurations.

## Materials and methods

### Greenhouse characteristics and climatic conditions

The experimental development was carried out in a multi-tunnel gothic greenhouse, the main characteristics of this structure are summarized in (Table 1). The greenhouse was built in the municipality of Mosquera (2,560 msnm), savannah of Bogota, Colombia. The region has climatological characteristics where the average multiannual temperature is 13.50 °C, with average maximum and minimum values of 22.3 and 4.4 °C and high humidity conditions generally above 75%. The annual precipitation reaches a value of 649 mm, presenting a bimodal behavior with maximum values for the months of March, April, October and November (Figure 1A). The average wind speed varies in the year between 0.2 and 1.6 m s<sup>-1</sup>, with predominant directions between 90 ° and 140 ° (Figure 1B).

**Table 1.** Constructive characteristics of greenhouses studied.

Characteristic	
Area (m <sup>2</sup> )	4704
Total width (m)	56
Total length (m)	84
Number of the spans	6
Span width (m)	9.3
Minimum height under gutter (m)	4.6
Maximum height under gutter (m)	7.9
Minimum height at ridge (m)	7.8
Maximum height at ridge (m)	11.1
Length of the rooftop vent (m)	1.5
Length of the sidewall vent	3.9



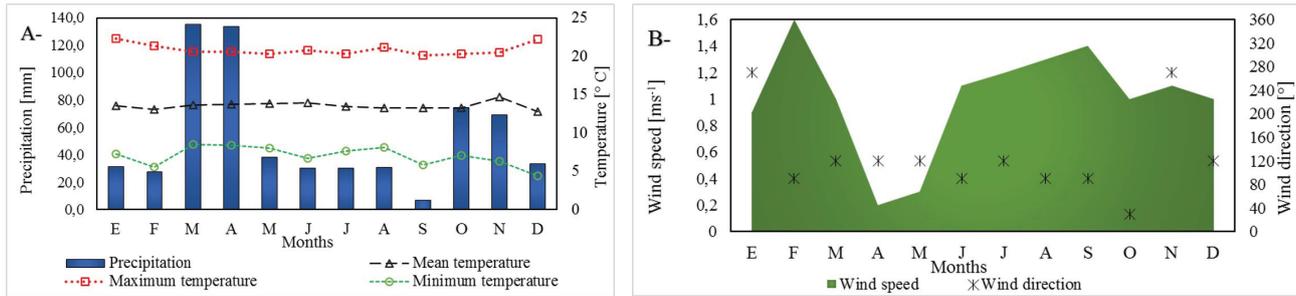


Figure 1. A) Multiannual climograph and B) Wind speed and direction for the study area.

### Fundamental computational aerodynamics

The commercial software ANSYS-Fluent was used to calculate the air flows and the distribution of humidity and temperature inside the structure. The movement and heat transfer of a fluid can be described mathematically using the Navier-Stokes equations:

$$\frac{\partial \rho \varphi}{\partial t} + \nabla \cdot (\rho \varphi \vec{v}) = \nabla \cdot (\Gamma \nabla \varphi) + S \varphi$$

where  $\vec{v}$  is the velocity vector ( $\text{m s}^{-1}$ ),  $\Gamma$  is the diffusion coefficient ( $\text{m}^2 \text{s}^{-1}$ ),  $\rho$  is the density of the air ( $\text{kg m}^{-3}$ ),  $\nabla$  is the divergence operator,  $\varphi$  represents the concentration of the transported quantity in a dimensional form (the momentum, the scalars mass and energy conservation equations) and  $S$  represents the source term (Piscia et al., 2015).

The above equation is solved by the finite volume method for the steady state condition and in each control volume ( $\Delta V$ ) its integral form is represented as follows:

$$\int_V \nabla \cdot (\rho \varphi \vec{v}) dV = \int_V \nabla \cdot (\Gamma \nabla \varphi) dV + \int_V S \varphi dV$$

The turbulent nature of the airflow was simulated using the standard turbulence model  $k-\epsilon$  with standard wall functions, this model has been widely used and validated in natural greenhouse ventilation studies (Teitel and Wenger, 2014; Bournet et al., 2017). The buoyancy effects influenced by the change in air density will be present (Espinal-Montes et al., 2015) and can be modeled through the Boussinesq model, which is described by the following expression:

$$(\rho - \rho_0) g = -\rho_0 \beta (T - T_0) g$$

Moisture behavior and mass conservation was modeled from the following expression:

$$\nabla \cdot (\rho Y_i) = -\nabla J_i + R_i + E_i$$

where  $E$  is the term source of moisture,  $J_i$  is the diffusion flow of the species,  $R_i$  is the production rate of species by component  $i$ ,  $Y$  is the local mass fraction of each species through the solution of the convection-diffusion equation.

### Computational domain and boundary conditions

The ANSYS-ICEM software was used to build a computational domain of sufficient size to allow the develop-

ment of airflow and an adequate definition of the atmospheric boundary layer. This computational domain, which included the greenhouse and its surrounding outdoor environment, had dimensions of: 225 m width ( $x$ -axis) and 70 m height ( $y$ -axis), was built following the recommendations given by Kim et al. (2017). In the mesh generation process, an unstructured grid of square elements with a total of 1,021,713 elements is selected, this grid was selected after verification of independence of the numerical solution of the grid size. The quality of the mesh was evaluated finding that 95.2% of the elements present high quality for the cell size parameter and the size variation between neighboring cells (ANSYS, 2017). A semi-implicit method for pressure equations was adopted to solve the pressure-momentum coupled equations using the SIMPLE algorithm. The convergence criterion was  $10^{-6}$  for the equations of energy, continuity, momentum and turbulence (Baxevanou et al., 2017).

The upper limit of the domain was fixed with boundary conditions of symmetrical properties, so as not to generate friction losses of the air flow in contact with this surface, the output limit on the leeward side was set with pressure-out condition. The simulations considered the atmospheric characteristics of the experimental site, such as the atmospheric pressure of 74,286 Pa, air viscosity equal to  $1.7E^{-05} \text{ kg m}^{-1} \text{ s}^{-1}$  and gravity of  $9.8 \text{ m s}^{-2}$ . At the lower boundary and the greenhouse walls, a non-slip wall boundary condition was set. Other properties of polyethylene and agricultural soil, such as specific heat ( $C_p$ ), thermal conductivity ( $k$ ) and density ( $\rho$ ), were established, according to Villagrán et al. (2012). The windward edge was applied the entry speed condition, adjusting a logarithmic profile following the procedure recommended in (He et al., 2017).

To obtain patterns of air flow, thermal distribution and relative humidity independent of parameters such as sowing density, established variety and vegetative state of the crop, the greenhouse was simulated without the presence of ornamental plants neglecting the effects of heat transfer and mass that plants contribute to the microclimate generated.

### Experimental data collection

To validate the model, an experimental process was carried out that included the recording of hourly climatic variables in the external environment of the greenhouse, such as air temperature and humidity, wind speed and direction, solar radiation, with using of a climate system Vantage

Pro2 (Davis Instruments, Hayward, CA, EE. UU.). Inside the greenhouse on the cross-section (x-axis), at a height of 1.7 m above ground level (y-axis), six sets of two copper thermocouples, used to measure wet and dry bulb temperatures, were uniformly installed and stored in a data logger (Cox-Tracer Junior, Escort DLS, Edison, NJ, EE. UU.). Outside and inside the greenhouse the measurement frequency was every 10 minutes, in the period from 04 to 27 September 2017.

The data obtained during the measurement period were analyzed, selecting those of a specific hour of the day (hour 13), the selection criterion was that these data allowed to develop a simulation when the wind was almost perpendicular to the longitudinal axis of the greenhouse, this simulation was developed with temperature values of 19.9 °C, relative humidity of 73% and a solar radiation of 567 W m<sup>-2</sup> under a RSV ventilation configuration with external wind speed of 0.92 m s<sup>-1</sup>. Once the simulation was finished, the post-process was carried out extracting the data of temperature and relative humidity of the interior air in the points x, and that coincided with the internal points of sampling, the data obtained by means of simulation and experimental

tion were compared through the calculation of the absolute mean error (MAE) and root-mean-square error (RMSE).

$$MAE = \frac{1}{m} \sum_{i=1}^m |V_{mi} - V_{si}|$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^m (V_{mi} - V_{si})^2}{m}}$$

where  $V_{mi}$  y  $V_{si}$ , are the observed value and the simulated value respectively and m the number of data compared.

### Scenarios considered

Numerical airflow simulations were performed for three configurations of ventilation, side ventilation (SV), roof ventilation (RC) and combined roof and side ventilation (RSV), evaluating different outside wind speeds (Table 2). The temperature and relative humidity selected as initial conditions corresponded to the maximum historical values present in the study area, their values were 22.3 °C and 80% respectively and were kept constant in each simulated case.

**Table 2.** Simulation scenarios evaluated.

Scenarios	Wind speed (m s <sup>-1</sup> )	Simulation configuration
SVV1	0.2	
SVV2	0.5	
SVV3	1.0	
SVV4	1.6	
RVV1	0.2	
RVV2	0.5	
RVV3	1.0	
RVV4	1.6	
RSVV1	0.2	
RSVV2	0.5	
RSVV3	1.0	
RSVV4	1.6	

## Results and discussion

### Model validation

The behavior of the simulated and measured values is shown in (Figure 2). In general, it is observed that the simulated data present a smaller magnitude than the measured data, although the spatial behavior in the transverse axis of the greenhouse exhibits a similar trend. The values ob-

tained from MAE and RMSE for temperature were 0.44 and 0.47 °C, while for relative humidity 3.99% and 4.04% were obtained, values that are within the range obtained in previous studies such as that developed by He et al. (2017). The above leads to the conclusion that the CFD model makes satisfactory predictions and can therefore be used to study the distribution of temperature, relative humidity and airflow in the contemplated greenhouse.

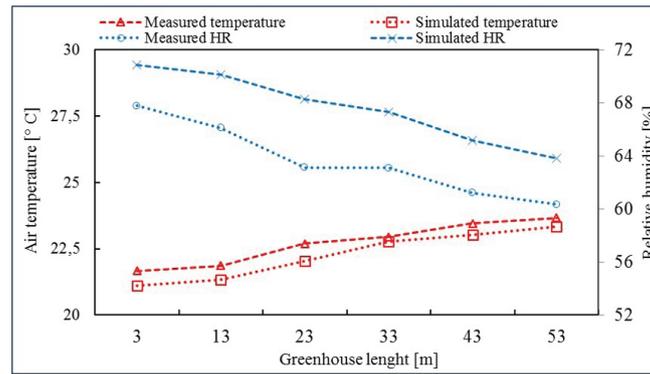


Figure 2. Simulated and measured temperature [° C].

### Ventilation rates and air flow fields

The airflow patterns for each configuration and velocity evaluated are shown in (Figure 3 A-D). In the case of SV, it is observed that there is an air movement across the width of the greenhouse from the windward side opening to the leeward ventilation. These air currents have average speeds of 0.31, 0.70, 1.22 and 1.87 m s<sup>-1</sup> for SVV1, SVV2, SVV3 and SVV4 respectively, it is also observed that under this configuration there are areas where there is no air movement, specifically around the deck of spans 1, 3 and 5, this situation is clearly generated by an inefficient mixture of air flow. The air distribution patterns for VR show a behavior with three differentiated regions with convective movement characteristics between the ground surface and the greenhouse cover. The first movement cell occupies the volume covered under span 1, while the remaining cells are distributed in the volumes of spans 2 and 3 and between

spans 4,5 and 6. This type of behavior is generated from the operation of fixed roof vents, which have a function of air flow inlet and outlet areas together with the changes in air density inside the greenhouse, generate a more important fluid mix than the SV scenario, the mean velocities calculated for RVV1, RVV2, RVV3 and RVV4 were of 0.36, 0.75, 1.09 and 1.54 m s<sup>-1</sup>. The flow patterns with the highest mean velocity were found in the RSV scenario, obtaining values of 0.39, 0.79, 1.34 y 1.98 m s<sup>-1</sup> for RSVV1, RSVV2, RSVV3 and RSVV4. Under this ventilation configuration the air flows into the greenhouse through the windward side window and the roof windows of the first three spans, this generates a movement of air that moves through the lower part of the structure that mixes with the air from the deck in spans 2, 4 and 5 to finally leave the greenhouse through the leeward side window and through the zenithal windows of spans 5 and 6.

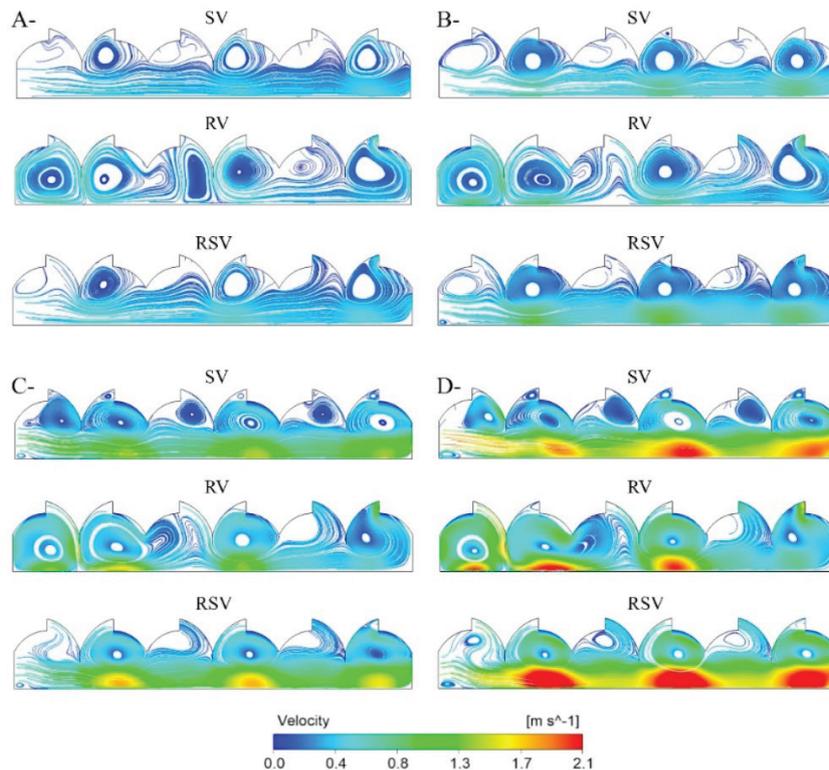


Figure 3. Wind speed profiles of simulations performed under wind speeds of 0.2 (A), 0.5 (B), 1.0 (C) and 1.6 (D) m s<sup>-1</sup>.

Ventilation rates ( $\Phi$ ,  $\text{m}^3\text{m}^{-2}\text{s}^{-1}$ ) for each evaluated configuration were calculated (Figure 4). The values obtained from  $\Phi$  for RSV range from 0.044 y  $0.182 \text{ m}^3\text{m}^{-2}\text{s}^{-1}$  for RSVV1 and RSVV4 respectively, this ventilation configuration is the one with the highest values from  $\Phi$  which is in line with previous studies carried out in tunnel greenhouses (Espejel Trujano and López Cruz, 2013; He et al., 2015). For SV and RV it was found that the average reduction values of  $\Phi$  are in the order of 33.45% and 50.5% respectively, with minimum values of 20% and 45% for SVV4 and RVV2, which confirms the importance of side ventilation for outdoor air velocities higher than  $1.5 \text{ m s}^{-1}$  while roof-

top ventilation becomes relevant at air velocities lower than  $1 \text{ m s}^{-1}$ , due to the contribution of the thermal effect to the natural ventilation (Katsoulas et al., 2006). In general it can be observed that for the average climatic conditions of the area, the ventilation rates under the RSVV3 configuration exceed the minimum design value established for naturally ventilated greenhouses where,  $\Phi_{\min} = 0.04 \text{ m}^3\text{m}^{-2}\text{s}^{-1}$  (ASAE, 2008). This is important because it allows us to conclude that this type of greenhouse becomes an alternative of use to traditional Colombian structures which have deficiencies in their ventilation indexes (Villagrán et al., 2012; Villagran et al., 2018).

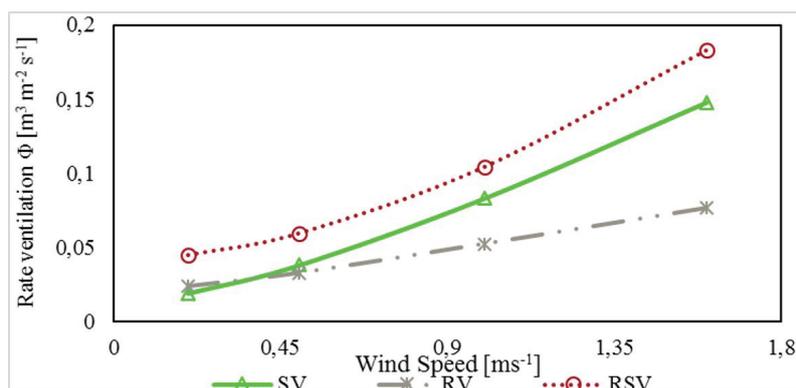
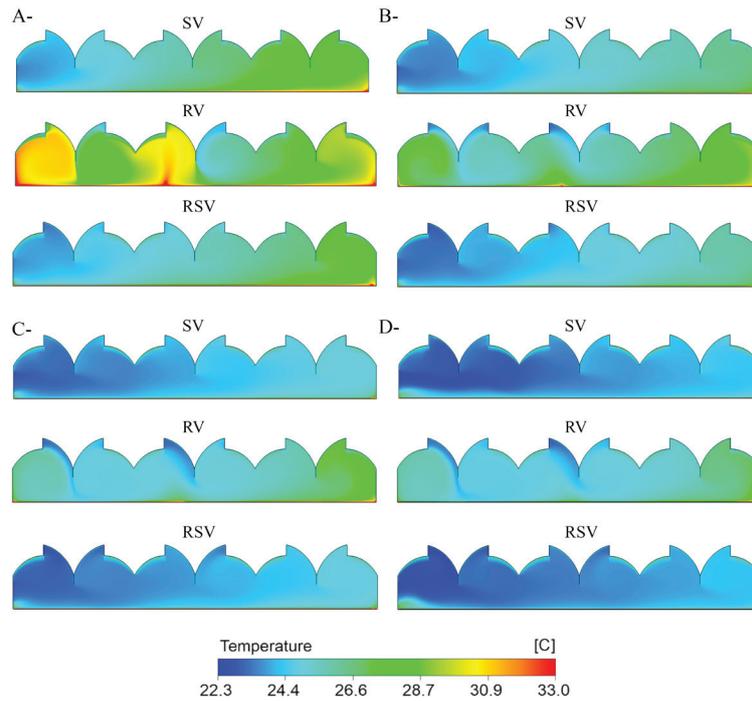


Figure 4. Ventilation rate  $\Phi$  [ $\text{m}^3 \text{m}^{-2} \text{s}^{-1}$ ] calculated for each simulated case.

#### Effect of natural ventilation on temperature behavior

Temperature is one of the main factors affecting the growth and development of rose cultivation, this parameter affects the process of photosynthesis in the plant and the floral development of this species (Shin et al., 2001). The spatial distribution of temperature inside the greenhouse for each evaluated scenario is shown in the (Figure 5). As a general result, an inverse relationship is observed between the ventilation rate and the temperature value, obtaining higher thermal values in the lower ventilation rate configurations, additionally it is observed how the zones lower temperatures coincide with the zones of entry outside air what agrees to previous studies carried out by Baeza et al. (2017). For rose production, it is recommended that the maximum daily temperature value, if possible, should

not exceed  $25 \text{ }^\circ\text{C}$ , since higher values in this range reduce the growing cycle with a loss of commercial quality of cut roses translated into shorter stems and flower heads of smaller diameter (Shin et al., 2001). Under these conditions it can be observed that for the predominant conditions of the study region that are represented by the SVV3, RVV3 and RSVV3 simulations, the optimal temperature requirement is met since the mean value obtained was of  $23,95 \pm 0,6$ ,  $24,98 \pm 0,71$  and  $23,98 \pm 0,58 \text{ }^\circ\text{C}$  (Figure 5C), similarly occurs with the scenario that evaluates an external wind speed of  $1.6 \text{ m s}^{-1}$  (Figure 5D). On the contrary, for low outside wind speed conditions that were represented by SVV1, RVV1 and RSVV1 the temperature value is higher than the optimum recommended in  $1.4$ ,  $1,76$  and  $0,62 \text{ }^\circ\text{C}$  respectively (Figure 5A).

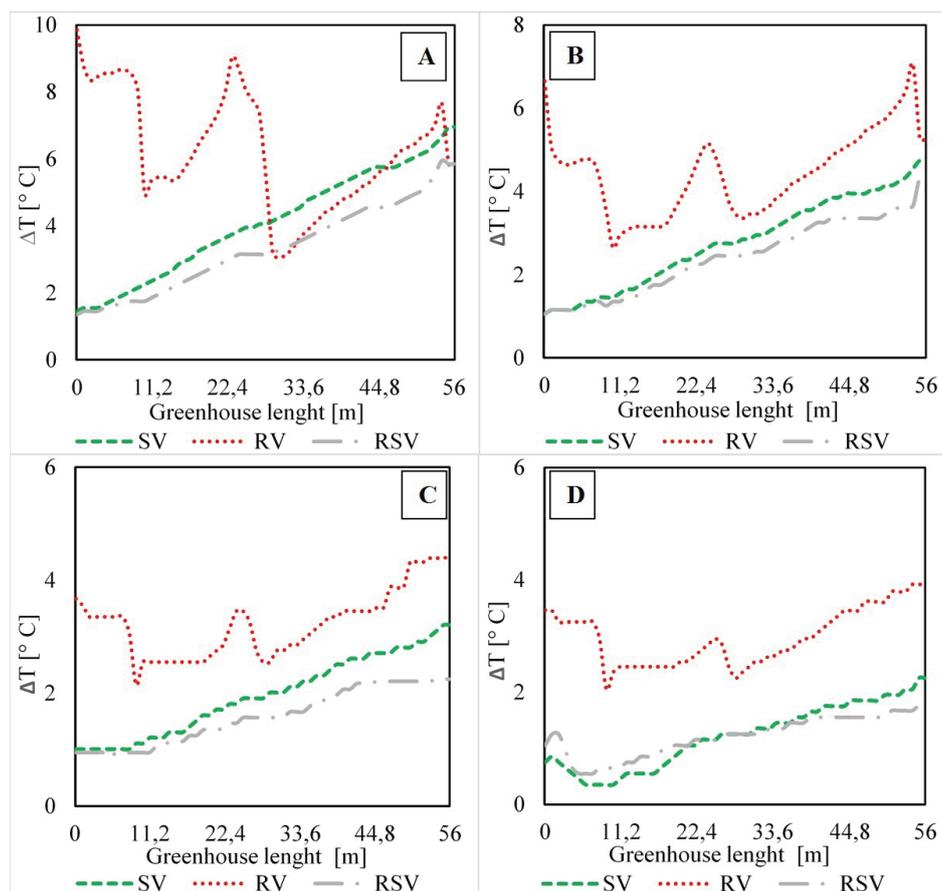


**Figure 5.** Temperature distribution profiles of the simulations carried out under wind speeds of 0.2 (A), 0.5 (B), 1.0 (C) and 1.6 (D)  $\text{m s}^{-1}$ .

In passive greenhouses activities such as irrigation, fertilization and harvesting are programmed uniformly for the entire covered area, for this reason another characteristic that is relevant to evaluate is the micro-climatic homogeneity inside the structure, since high values of both thermal differentials and psychometric characteristics of the air between one region of the greenhouse and another can significantly affect the growth and development of plants. This assessment was made by calculating the thermal gradient ( $\Delta T$ ) for all the simulations developed,  $\Delta T$  represents the difference between indoor and outdoor air temperature.

The behavior of  $\Delta T$  was calculated at a height of 1.5 m above ground level across the transverse length of the greenhouse (Figure 6). According to the results, it is ob-

served that the RSV ventilation configuration is the most appropriate since it generates the values of  $\Delta T$  and the lowest variation in each of the simulated scenarios, on the other hand, the RV configuration is the one that generates the most heterogeneous thermal environment. For RSVV3 where the predominant external wind speed was simulated it was found that the mean value of the generated  $\Delta T$  was of  $1.58 \pm 0.41$   $^{\circ}\text{C}$  (Figure 6C). While for RVV1 a  $\Delta T$  was obtained from  $6.26 \pm 1.87$   $^{\circ}\text{C}$ , having clearly two differentiated conditions in magnitude and thermal variation, which allows to conclude that RSV is the ventilation configuration that generates optimal airflow circulation patterns that are reflected in a homogeneous thermal behavior in the evaluated structure (Figure 6A).

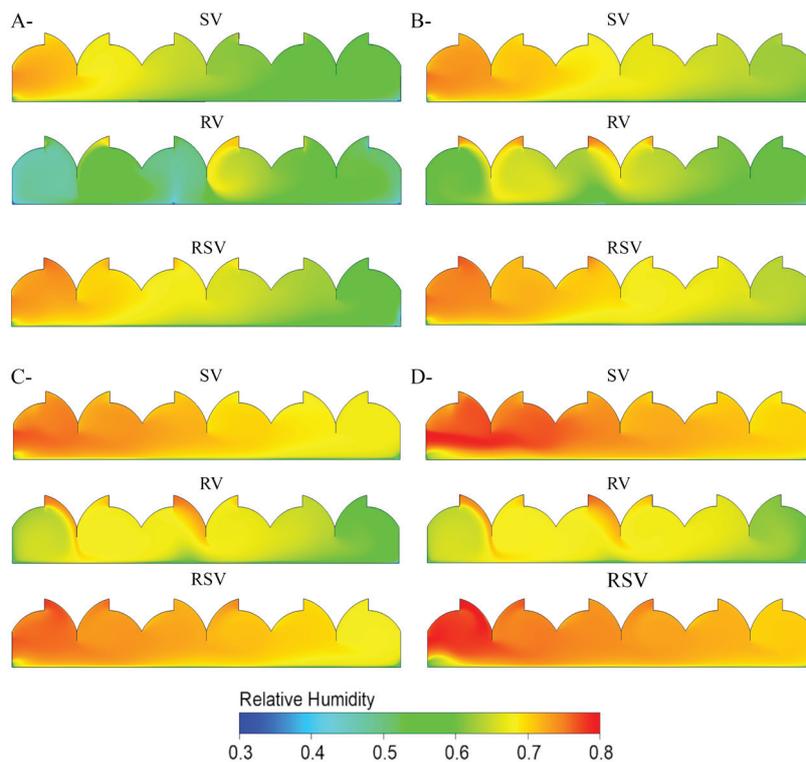


**Figure 6.** Thermal differential  $\Delta T$  [ $^{\circ}\text{C}$ ] calculated under wind speeds of 0.2 (A), 0.5 (B), 1.0 (C) and 1.6 (D)  $\text{m s}^{-1}$ .

#### Effect of natural ventilation on the behavior of relative humidity

Relative humidity is another of the key parameters that must be controlled inside greenhouses, this parameter directly influences the growth, yield and final quality of crops (Bouhoun Ali et al., 2014). In conditions of high humidity higher than 80% and some environmental conditions the phenomenon of condensation occurs, facilitating the presence of free water on the leaves of the plants favoring the appearance and development of fungal diseases or increasing the number of soft and thin leaves with necrosis problems. These same humidity conditions combined with low vapor pressure deficit values reduce the transpiration rate of the plant, generating physiological disorders due to the translocation of some nutrients. On the other hand, conditions with relative humidity below 40% increase the tran-

spiration of the plants, which can favour damage due to hydric stress (Bournet, 2014). Relative humidity distribution profiles show that for simulations with wind speed of 0.2 and 0.5  $\text{ms}^{-1}$  there is a behavior with a marked heterogeneity with differential values of up to 33% between one region and another, as is the case of RSV1, for this configuration was obtained an average humidity value of 54.82% (Figure 7A). Regarding the behavior for the predominant conditions in the region, humidity values of  $71.33\% \pm 3.02\%$ ,  $64.75\% \pm 3.43\%$  and  $71.82\% \pm 2.51\%$  for SVV3, RVV3 and RSVV3 were obtained, lo which certifies that values greater than 60%, minimum value recommended in rose production, would be obtained (Yong, 2004) (Figure 7C). For these configurations a homogeneous moisture behavior is also observed, which is directly related to appropriate ventilation rates and uniform air flows.



**Figure 7.** Relative humidity distribution profiles of the simulations carried out under wind speeds of 0.2 (A), 0.5 (B), 1.0 (C) and 1.6 (D) m s<sup>-1</sup>.

## Conclusions

A numerical CFD-2D model, solved by finite volume methodology, was used to study air flows and their effect on microclimate in an alternative greenhouse for the high Andean tropics. The model was validated through experimental measurement, showing an adequate fit between simulated and measured data, which allowed the analysis of three configurations of SV, RV and RSV ventilation. The results obtained showed that for the study region the RSV ventilation configuration generates ventilation rates higher than the minimum recommended for passive greenhouses ( $\Phi_{\min} = 0.04 \text{ m}^3\text{m}^{-2}\text{s}^{-1}$ ), which generates an appropriate and homogeneous behavior of the temperature and relative humidity variables for rose production.

### Author contribution

**E.A.V.M.**<sup>0000-0003-1860-5932</sup>: idea of creation, development of numerical simulations, data analysis and collection, preparation of manuscript. **C.R.B.A.**<sup>0000-0003-0230-326X</sup>: lead and install the experiment, prepare the manuscript.

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