Chapter

CFD Simulation of Heat and Mass Transfer for Climate Control in Greenhouses

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Abstract

Greenhouse plant production involves a number of processes such as transpiration, condensation, photosynthesis, and climate control. Such processes, in turn, set off mass and heat transfer phenomena that influence not only the quality and quantity of crop production but also its environmental cost. While these processes have considerably been analyzed in separate, they strongly interact with one another. For instance, increased radiation (mainly thermal infrared) increases temperature, reduces humidity, consequently increases transpiration, and affects CO_2 exchange as well as other reaction rates. Computational fluid dynamics (CFD) is a numerical tool with a solid physical basis which allows, through the construction of a computational model, to simulate the fluid flow environment. Heating, ventilation, and condensation have been analyzed in the greenhouse environment with CFD techniques. The current challenge is the interaction of these processes and their impact on the production system. The present work summarizes some CFD investigations carried out in this topic, in order to analyze the processes of heat and mass transfer in a greenhouse for agronomic purposes.

Keywords: ventilation, heating, crop production, numerical simulation, climate control

1. Introduction

The fast expansion of greenhouse technique around of world, as a means to supply food and produce, has posed emerging challenges in the operation and management of greenhouse climate. While such challenges have not changed in essence ever since the onset of agriculture, they have been considerably reshaped by the access to new technologies and information.

In semiarid regions, the main problems are the high temperatures that take place in daily and annual cycles. The same is true for cold temperatures. There are many options to auxiliary climate control systems, the implementation of which depends on many factors such as their cost, crop, location, and management, to name a few.

Greenhouse is an advantageous production system which realistically allows us to produce crops from all over the world during the whole year. Consequently, environment interior conditions such as temperature and humidity have to be controlled at a certain plant-specific level regardless of environmental conditions.

In greenhouse crop production, climate has peculiar considerations, because the most important data is the impact of the environmental factors on the crop cycle. The cultivation of plants requires a sufficient amount of light, a specific range of temperature, humidity, and CO_2, among other requirements. These requirements are primarily influenced by the greenhouse design and size and vary according to the local climate conditions. For instance, the radiation quantity inside the greenhouse depends on whether greenhouses are built with PVC or glass, because the surface material is the element to optimally use solar radiation for the required lighting [1].

Recently, heating, ventilation, and air conditioning (HVAC) systems have been extensively used in urban spaces, such as offices or stores, at agriculture area, and specifically in greenhouses. For instance, HVAC has been used in buildings in order to analyze the optimization and comfort inner Officine's and several uses. In greenhouses, the concept is incipient, even though the application of the ventilation and calefaction systems as a method to climate control in cold and warm regions is nothing new.

The climate produced in a greenhouse is the result of complex mechanisms involving the processes of heat and mass exchange. The internal climate is strongly dependent on the outside conditions, especially in unheated greenhouses. In greenhouse climate models, the parameters of the internal climate such as air, soil, and crop temperatures as well as air humidity are calculated using energy and water vapor balances for the various components of the system [2].

Climate in the greenhouse is a consequence of radiation crossing the cover material, usually plastic. After that, climate condition is a strong relationship between several factors, temperature, humidity, wind velocity, and the solar radiation. Environment conditions in the greenhouse depend on the energy management, by the auxiliary calefaction and ventilation systems. The equilibrium of these climate variables is a function of the efficiency of air exchange generating losses and gains of heat (temperature, radiation) and mass (humidity, gases) [3].

The automation in a greenhouse environment involves climate control, light-level control, and shade curtain management; gases inside the greenhouse are due to the plant reactions with the environment, requiring control of carbon dioxide (CO_2) concentration, irrigation and chemical treatment. Greenhouse automation is a modern, efficient, and accurate disruptive agriculture, which utilizes data collected within the system, to obtain better quality and higher yields, thereby increasing productivity [3].

Every process inside the greenhouse consumes energy and involves a change of mass between the sink or the source. The objective of this work was to show some results on greenhouse mass and energy transfer, using CFD.

2. Computational fluid dynamics (CFD) in a greenhouse simulation

Computational fluid dynamics (CFD) is an analysis tool based on numerical methods that show graphically the general and localized air movement inside the greenhouse owing to natural ventilation. Also, it is possible to determine spatial temperature distributions arising from such air movement, all this for any greenhouse type and open/closed configuration of the roof and side windows.

CFD modeling of different parameters in greenhouses has been used to examine various features such as vent configuration [4]; natural and mechanical ventilation [5, 6]; ventilation in screenhouses [7]; condensation, transpiration, and heat and mass transfer [8–10]; and, more recently, calefaction and HCVA [11] and their interactions [12, 13]. The analyses of these systems allow for climate control,

Figure 1.
Natural and mechanical climate control in greenhouses.

thereby offering the possibility to provide large numbers of high-quality crops with greater predictability.

CFD modeling has been used as a tool to get major details in facilities, for instance [14], uses CFD to analyze ventilation system in greenhouses. Based on CFD, simulation is possible to optimize some characteristics of ventilation systems, such as relationship between volume and vent area of greenhouses [15].

The performance of ventilation in enclosed spaces is affected by the flow of outside air [16], type of cover, height of the installation, and the ventilation opening [18]. Computational parametric studies on greenhouse structures can aid to identify design factors that affect greenhouse ventilation under specific climatic conditions [5, 19].

Modern auxiliary systems used for climate control demand new approaches of study, e.g., to quantify the effect of the back-wall vent dimension on solar greenhouse cooling. Traditional solar greenhouse (**Figure 1**) uses radiation to store energy and get advantages of its use naturally. Some studies [10] showed that it is possible to reduce averaged air temperature by approximately 1.7°C and the highest temperature drop by approximately 5.8°C, in comparison to a traditional solar greenhouse with brick back wall (TG). These authors also suggest that a back-wall vent of 1.4 m increased internal ventilation efficiency in a solar greenhouse by installing removable back walls [10].

On the other hand, modeling of climate systems is necessary for studying and regulating energy consumption and quality of indoor environment. In urban semi-closed spaces, modeling approaches are used in HVAC systems [20]. Physics-based models offer adequate capabilities for first-hand assessments but suffer from poor accuracy; data-driven models have very high accuracy on training data but suffer from lack of generalization beyond the training domain.

Numerical methods have also been implemented for analyses of crop production in semi-closed spaces. Santolini et al. [7] reviewed the effect of mass transfer in a screenhouse structure with CFD. Alternative computer-based simulation models have been used for examining typical greenhouses with alternative energies such as dynamic photovoltaic (PV) and plant cultivation [21, 22].

3. Heat and mass transfer equations and CFD simulations

Heat and mass transfer is investigated using CFD tools. A numerical model is built based on the solution of the governing equations for momentum, energy, and continuity within the greenhouse domain. General equations can be written as the convection-diffusion equation to simulate mass, velocity, temperature, or other variables inside the greenhouse (Eq. 1):

$$\frac{\partial\rho\varnothing}{\partial t}+\nabla\left(\rho\acute{v}\varnothing\right)=\nabla(\Gamma\nabla\varnothing)+s_{\phi} \quad (1)$$

where $\varnothing$ transport variable; u_j velocity vector (m s^{-1}); Γ_{ϕ} diffusion coefficient; s_{ϕ} source term to variable $\varnothing$ (temperature, CO_2, etc.).

Specific energy balance simulation is based on the solution of heat and mass balance equations applied to the whole greenhouse system [8].

For the heat balance of greenhouse air, the general equation is shown in Eq. (2):

$$\frac{\rho V C_p \Delta T}{\Delta T}=\sum\nolimits_1 q_i A_i+\phi\left(C_p T_{out}-C_p T_{int}\right) \quad (2)$$

Mass balance of greenhouse air is described in Eq. (3):

$$\frac{M_w}{\partial T}=\Gamma_{crop}-\Omega_{cov}+\phi\left(W_{air}-W_{air_{ou}}\right) \quad (3)$$

where ρ is the density (kg cm^{-3}); t is the time (s); T is the temperature (°C); C_p is the heat capacity at constant pressure; Φ is the ventilation rate (kg s^{-1}); W (kg m^{-3}); $\sum_1 q_i A_i$ (W) is the sum of the convective contribution; Γ_{crop} (kg s^{-1}) is the transpiration rate; w_{air} (kg kg^{-1}) is the inside humidity ratio; W_{air_out} (kg kg^{-1}) is the outside humidity ratio; M_w is the water vapor mass.

The energy transfer process can occur basically in three physical phenomena: radiation, convection, and conduction. In greenhouse inner, convective heat transfer is the main source of temperature and energy. The conduction of energy occurs from the soil layers, and the flow is displaced depending on the quantity, always from higher to lower.

3.1 Conduction energy transfer process

Heat conduction is based on Fourier's law, in which one direction is a simple Eq. 4:

$$q_x=-kA\frac{\delta T}{\delta x} \quad (4)$$

where k material conductivity (W m^{-1}); A cross-sectional perpendicular area (m^2); $\frac{\delta T}{\delta x}$ thermal gradient (°C).

The convective effect is calculated using the cooling Newton's law (in Eq. 5):

$$Q=hA_s(T_s-T_\infty) \quad (5)$$

where h convective heat transfer coefficient (W m^{-2}); A_s area (m^2); T_s surface temperature (°C); T_∞ fluid temperature (°C).

In a greenhouse, Eqs. (6) and (7) give the convective fluxes:

$$q_{conv,i}=\alpha_i(T_i+T_{air}) \qquad \left[\text{Wm}^{-2}\right] \quad (6)$$

$$Q_{conv,i}=A_i\alpha_i(T_i+T_{air}) \quad \left[\text{Wm}^{-2}\right] \quad (7)$$

3.2 Radiation: energy transfer process

Outgoing radiation from a surface with nonzero transmissivity cover and sidewalls can be described in Eq. 8 [23]:

$$j_{i-in} = \varepsilon_i \sigma T_i^4 + \zeta_i g_{in} + \tau_{in} g_{ext} \quad \left[\mathrm{Wm^{-2}}\right] \tag{8}$$

where ε_i is the emissivity, σ is the Boltzmann constant, ζ_i is the reflectivity, and τ is the transmissivity. The outgoing radiation from opaque surface, soil, external soil, and sky is calculated with Eq. 9:

$$j_i = \varepsilon_i \sigma T_i^4 + \zeta_i \quad \left[\mathrm{Wm^{-2}}\right] \tag{9}$$

Incident radiation on a surface is (Eq. (10)):

$$g_i = \sum\nolimits_{j-sup} F_{i\to j} J_j \quad \left[\mathrm{Wm^{-2}}\right] \tag{10}$$

where $F_{i\to j}$ is the view factor between surfaces j and i (Eq. (11)).

Several factors are involved in these calculations. For instance, the net radiation balance could be simulated with Eqs. (11) and (12):

$$q_{rad} = j_i - g_i \quad \left[\mathrm{Wm^{-2}}\right] \tag{11}$$

$$Q_{rad-i} = A_i \left(j_i - g_i\right) \quad [\mathrm{W}] \tag{12}$$

In addition, the ideal black-body radiation is shown in Eq. 13:

$$E_{b\lambda} = \frac{C_1}{\lambda^5 \left(e^{\frac{C_2}{\lambda T}} - 1\right)} \tag{13}$$

where $E_{b\lambda}$ spectral emissivity power (W m^{-2}); λ wave longitude (m); T absolute surface temperature (K); C_1 3.7405×10^{-16} (W m^2); C_2 0.0143879 m K.

The power surface emissivity is

$$E_b = \sigma T_s^4 \tag{14}$$

where T_s absolute surface temperature (K) and σ Boltzmann constant (5.6697×10^{-8} W m^{-2} K^{-1}).

The simulation of radiative heat exchange between black surfaces is based on Eq. 15:

$$Q_{1-2} = \sigma A_1 F_{12} \left(T_1^4 - T_2^4\right) = \sigma A_2 F_{21} \left(T_1^4 - T_2^4\right) \tag{15}$$

where F is the fraction of radiant energy that leaves the area A (m^2).

3.3 Mass transfer process in a greenhouse

In a greenhouse, the mass balance between inflows and outflows must be preserved. In general, Eq. 16 represents the mass balance:

$$\frac{\partial \acute{\rho}}{\partial t} + \frac{\partial}{\partial x_j}\left(\acute{\rho}\acute{u}_j\right) = 0 \tag{16}$$

where ρ air density (kg m^{-3}) and u_j wind velocity in j direction (m s^{-1}).

3.3.1 Condensation

Crop transpiration increases the percentage of water vapor in the environment, generating the possibility of obtaining saturated air. Environment saturation is an undesirable effect over the crops. There are some approximations in order to know condensation rate [8], which can be estimated as a difference between former quantity and the latter. Eq. (17) is used to estimate it:

$$\Omega_{cov} = \max(0, M_{w,air} - M_{w,\text{cov}})\ [\text{kg}] \tag{17}$$

where $M_{w,air}$ the humidity content of the greenhouse air (%) and M_{w,cov_in} the saturated humidity content of air at the cover temperature (%).

3.3.2 Water vapor

Water vapor transport is simulated with Eq. 18:

$$\frac{\partial(\acute{c})}{\partial t} + \frac{\partial}{\partial x_j}\left(\acute{u}_i\acute{c}\right) = \frac{\partial}{\partial x_i}\left(D_w + \frac{\mu_t}{\acute{\rho}s_{ct}}\right)\frac{\partial(\acute{c})}{\partial x_i} + S_w \tag{18}$$

where C mass concentration of component in air (kg kg^{-1}); u_i wind velocity in j direction (m s^{-1}); D_w water vapor diffusivity (m^2 s^{-1}); μ_t turbulence air viscosity (kg m^{-1} s^{-1}); ρ density (kg m^{-3}); S the average velocity module in the deformation (m s^{-2}) which is calculated with Eq. 19:

$$S_w = \frac{ET}{Lv}LAD \tag{19}$$

where ET latent heat flux density (W m^{-2}); Lv evaporation latent heat (J kg^{-1}); and LAD leaf area density (m^{-1}).

4. CFD simulations in greenhouses

4.1 Natural and mechanical ventilation

In a greenhouse crop production, the ventilation system is the most important auxiliary equipment for climate control. Natural or mechanical ventilation design accounts for the size of greenhouse to determine the vent dimension and position (**Figure 1**). Furthermore, new complementary devices have been adapted to enhance the efficiency of air renewal rates. For instance, the use of the back-wall vent dimension on solar greenhouse cooling was investigated by He et al. [10] using CFD. In this study, the average air temperature in a solar greenhouse with removable back walls (RG) was reduced by approximately 1.7°C with a back-wall vent of 1.4 m, thereby increasing ventilation efficiency.

The presence of screens in the lateral and roof windows reduces the ventilation rate. However, according to [7], screens promote uniform velocity distributions inside the greenhouse compared to no-screened greenhouses, especially near the crops. **Figure 2** shows the results of a CFD simulation in a screenhouse, more specifically the exchange of air inside/outside near the screenhouse roof.

The advantages of numerical simulation are the possibilities to observe details in specific zones of the greenhouses (**Figure 2A**) and to convert a discrete phenomenon continuously. **Figure 2B** shows the mass air that enter and exit from a screenhouse under five exterior velocities simulated, when crop is simulated and empty. When the screenhouse is empty, mass balance is very similar; however, the crop reduces this flow until 200 kg s^{-1} when exterior wind velocity is 5 m s^{-1}.

In a greenhouse with combined mechanical and natural ventilation (**Figure 3**), the velocities' patron is marked different. For instance, when only mechanical ventilation (fist one) is simulated, temperatures' distribution is basically due to mechanical convection as a consequence of these air movements. In the second one, roof windows are 30% open and the wind patron changed. If just mechanical ventilation is working, under vents, the velocity is near to zero, but if the roof windows are open, the wind distribution is better than only mechanical ventilation.

CFD simulation of the ventilation systems, natural, mechanical, or combined, allows to observe the distribution of the air in a problematic zone and infer process of mass and energy transfer due to the interaction with the external climate conditions.

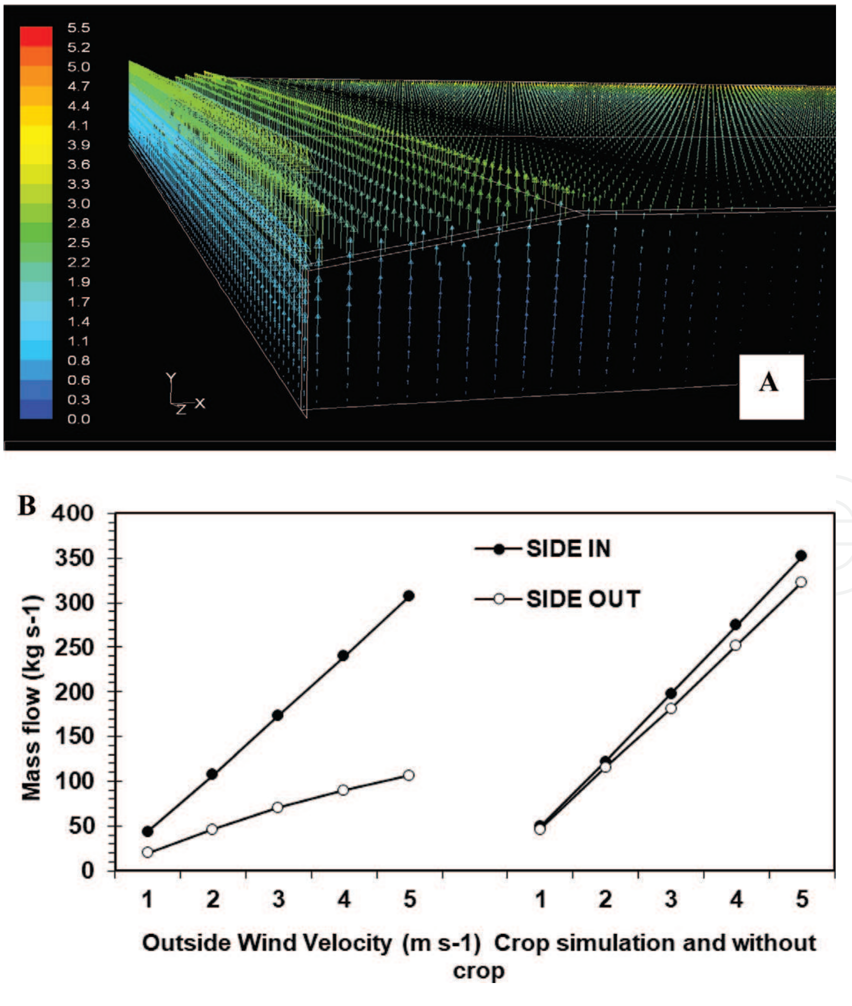

Figure 2.
(A) Top view of mass exchange in the roof of screenhouse and (B) scalar mass flow (kg s^{-1}) side exchange (inside/outside) by CFD simulation with and without crop.

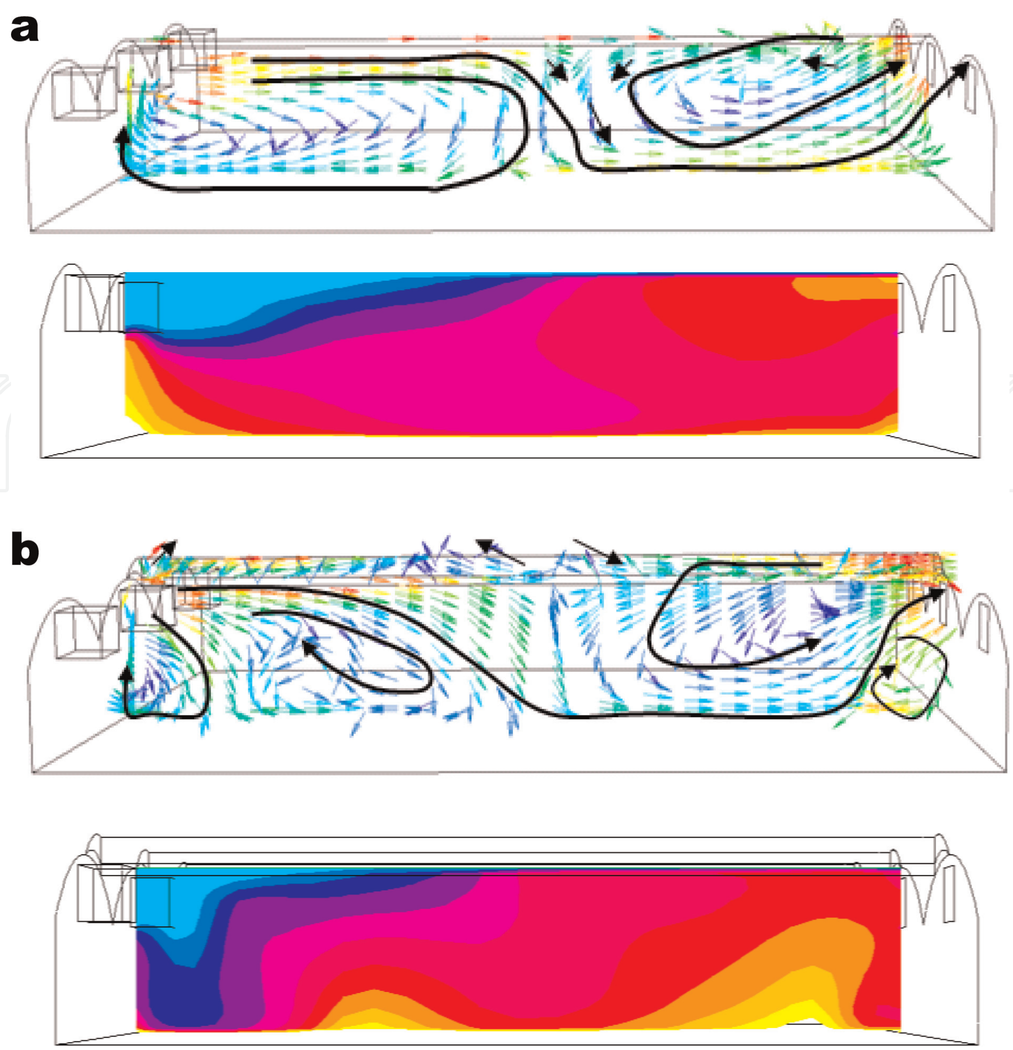

Figure 3.
Wind velocity vectors' distribution in the central spans of greenhouse closed (A) and all-open (B).

4.2 CFD heating pipe tube simulation

Heating in greenhouses strongly influences crop yields [17], energy consumption, and operation costs; however, this type of systems is essential to achieve sustainable production. A method to prevent low temperatures below a threshold makes use of the forces arising from a temperature or convection gradient.

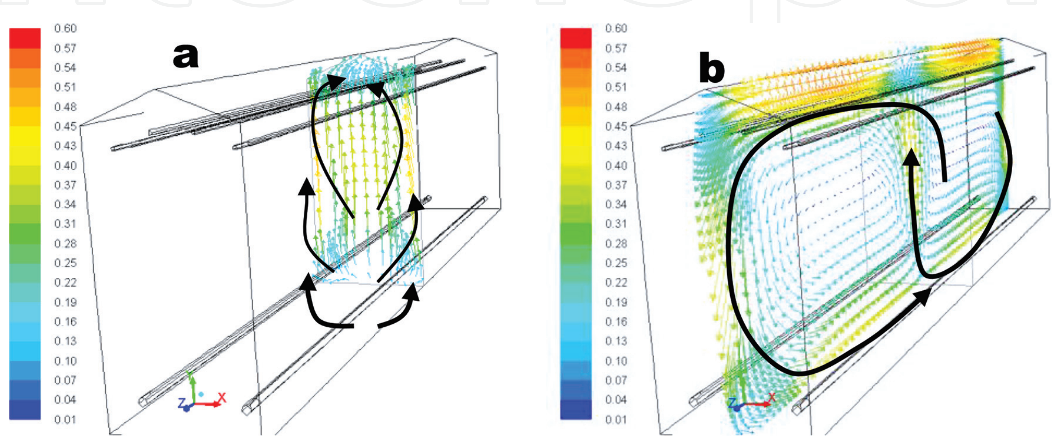

Figure 4.
Distribution of wind speed vectors (m s^{-1}) to the center of the module in a frontal (a) and longitudinal (b) plane.

The systems that most cold-climate greenhouses use are a collector wall and a heating system based on water or gas driven by a pipe. The heating pipes (pipe heating) is an effective means of keeping the greenhouse warm by promoting convection and radiation of heat. The layout of these tubes and the heating power determine the spatial distribution of temperature and the flow patterns induced by the movement of air due to the convective effect (**Figure 4**).

Teitel et al. [24, 25] mentioned that the best way to place the tubes is at medium height and under the crop, with the tubes as close as possible to the leaves. Other configurations have been analyzed by various researchers [24, 26, 27], which highlight the influence of the heating system with crops and radiative aspects. These investigations have unveiled the advantages of installing hot water pipes (pipe heating) in the lower part of the crop without promoting excessive evaporation [28]. Such pipe heating systems also favor the removal of humidity, which is known to negatively influence air quality. Moisture transport has been analyzed using computational fluid dynamics (CFD) to address various aspects such as condensation [8] and refrigeration [18], especially in closed greenhouses [5].

Numerical methods have been widely used to study climate variable inner greenhouses [29]. In 2007 and recently 2017 [30, 31] analyzed the heat distribution by three pipes and perforate polyethylene ducts to manage low temperature in tomato crop greenhouses. CFD gets observed as strong thermal gradients near to the ground and roof and well conditions in the crop zone. In this study, the effect of determining the flow and temperature patterns is the location and power of heating devices [31].

Figure 4 shows the air movement in a small greenhouse, with heating system based on five heat water tubes. The air movement and energy transference are due to the convection method, because temperature in the low tubes is higher than the upper pipe tubes. Normally wind velocities in greenhouse oscillation are between 0.1 and 0.5 m s^{-2}, due to pressure effect. In this system, wind velocity, just for convection effect, is 0.2–0.3 m s^{-1}.

A homogeneous temperature distribution is observed throughout most of the day (**Figure 5**). In a greenhouse almost all of the management processes need energy; in fact, in cool regions, the cost due to the climatic control is nearly 40% of the total production cost or more, depending on the automation grade of sensors and controls.

4.3 Transpiration

Transpiration is a special component with enormous importance in the balance of energy and transfer process in the greenhouse system. Crop transpiration is an important process useful not only in the production process but also in the climate

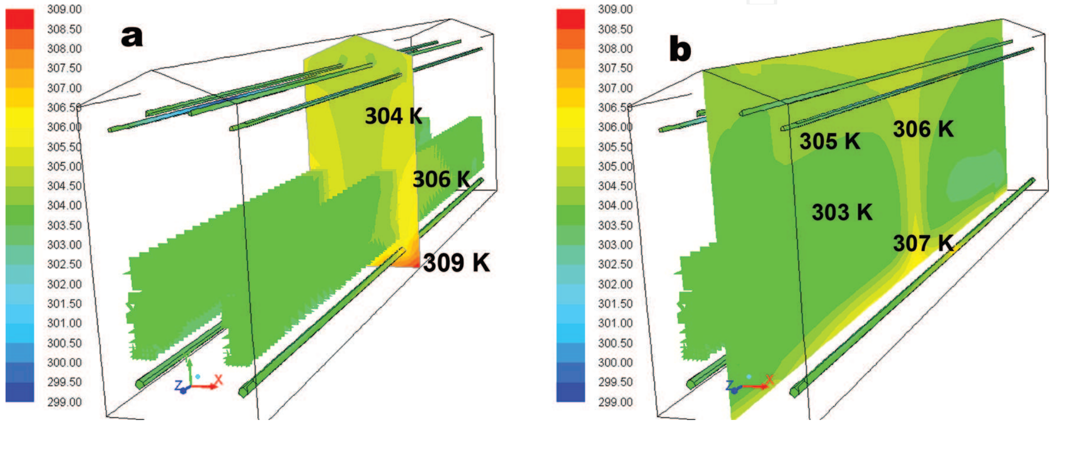

Figure 5.
Temperature gradient (K) to the center of module: frontal plane view (a) and longitudinal plane view (b).

control. Actually, transpiration is the first cooling natural system; when the high temperature is increasing, transpiration occurs very fast, and temperature is controlled. In CFD it is possible to simulate this phenomenon as a source term from the crop, as a flow of water. To speed up energy transport calculus use the model Penman-Monteith (Eq. 20) with some simplification.

Simulation in Fluent is based on Eq. 20, and for the simulation of transpiration, it is necessary to make a balance of energy between the plant and the environment, creating a system of equations implemented in the simulation as a "user-defined function" (UDF) so that terms such as transpiration, the consumption of CO_2, etc. can be calculated [4]. Nowadays most of the factors and estimated values of latent heat of vaporization in the energy balance equation can be measured using data of density, thermal conductivity and psychometric constant.

$$ET = \frac{\Delta(Rn - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left[1 + \frac{r_c}{r_a}\right]} \tag{20}$$

where ET is the potential evapotranspiration (kg m^{-2} s^{-1} o mm s^{-1}); Rn is the net radiation (kW m^{-2}); G is the heat flux in soil (kW m^{-2}); $(\boldsymbol{e_s} - \boldsymbol{e_a})$ is the vapor pressure deficit (kPa); $\boldsymbol{r_c}$ is the crop resistance (s m^{-1}); $\boldsymbol{r_a}$ is the aerodynamic resistance (s m^{-1}); $\boldsymbol{\Delta}$ is the slope of the vapor pressure saturation (es/T) (Pa °C^{-1}); $\boldsymbol{\rho_a}$ is the air density (kg m^{-3}); $\boldsymbol{c_p}$ is the specific heat of the air (MJ kg^{-1}°C^{-1}); and $\boldsymbol{\gamma}$ is the apparent psychometric constant (kPa °C^{-1}).

In the case of stomatal resistance, it is possible to measure it directly and relate it to the environmental variables involved (solar radiation, VPD, temperature and CO_2 concentration). For each crop, the resistance will be different, but in general an average resistance in the canopy can be estimated according to the foliar area index [33]. To estimate external leaf resistance, it has been assumed that temperature of the leaf and air is the same, so it is possible to estimate a coefficient r_c with Eq. (21):

$$r_c = \frac{r_i}{L} \tag{21}$$

where R_c is the internal resistance of the leaf canopy to the transfer of water vapor (s m^{-1}), L is the leaf area index, and r_i internal resistance of the leaf (s m^{-1}). **Figure 6** shows the simulated results of the distribution of humidity and mass fraction along the greenhouse using the simplified model of [33]. Numerically it was demonstrated that the Penman-Monteith transpiration model is not particularly sensitive to the variables with the simplification of the model mentioned, which can be an indication of a good result.

Transpiration of the crop is directly affected by the foliar area (**Figure 7**), and consequently the strict relationship between this and the vapor pressure deficit (VPD) will be the variable to follow for an approximation to the transpiration of greenhouse crops.

The largest source of variation between the models compared is based on the leaf area of the crop; while it is true that transpiration is originally associated with the amount of radiation, the dependence of stomata in this exchange is also founded. **Figure 7** shows the variation of the transpiration of the crop as a function of the leaf area index (LAI), in this case a tomato crop.

4.4 Gas simulation (ammonia)

Mass transfer in semi-closed spaces is an important process. Ventilation is the primary mechanism for gas removal. Air movement assumes a mixture of liquid,

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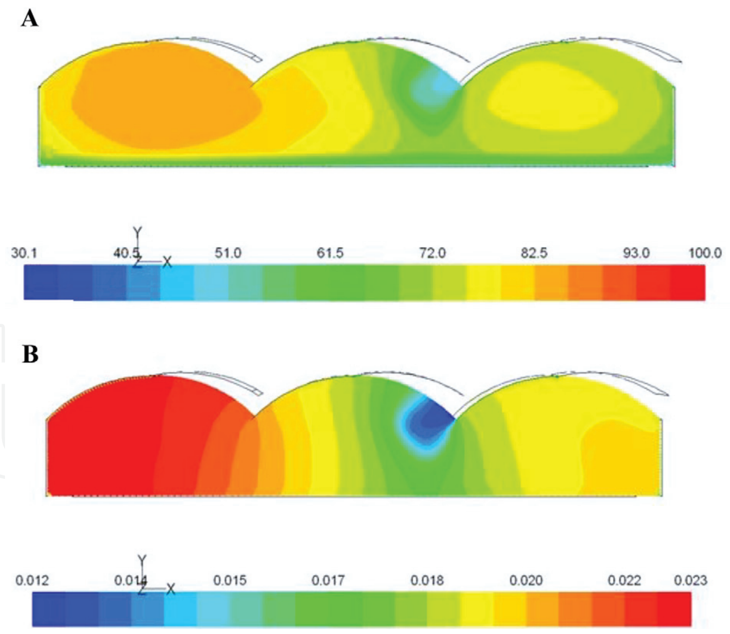

Figure 6.
Contour of relative humidity (%) (A) and transpiration as a mass fraction of H_2O (B) using CFD simulation [33].

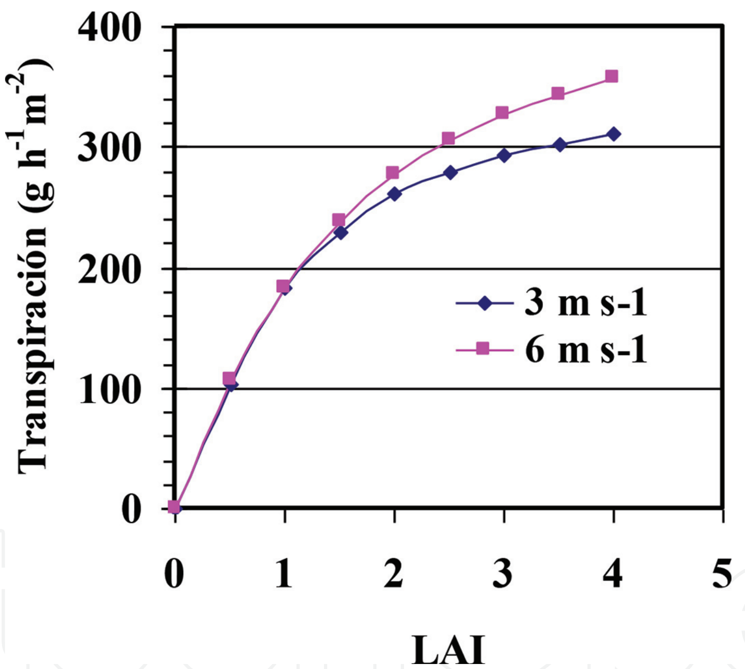

Figure 7.
Variation of transpiration (g m^{-2} h^{-1}) of a tomato crop as a function of the leaf area (IAF), when 3 and 6 m s^{-1} speed is simulated outside of the wind [33].

vapor, and nonconsumable gases. In this case, the species transport model available in ANSYS Fluent was used to simulate the mass transport, beginning from the diffusion flux of species i, which arises due to gradients of concentration and temperature. Such species model uses the dilute approximation (Flick's law) to model mass diffusion. For turbulent flows, mass diffusion can be written as in Eq. 22 [32]:

$$\bar{J}_i = \rho D_{i,m} \nabla Y_i - D_{T,i} \frac{\nabla T}{T} \tag{22}$$

In Eq. (19), J_i is the diffusion flux of species i (m^2 s^{-1}), ρ is the density of the mixture (kg m^{-3}), $D_{i,m}$ is the mass diffusion coefficient for species i in the mixture *m* (m^2 s^{-1}), and $D_{T,\,i}$ is the turbulent diffusion coefficient (m^2 s^{-1}). *Yi* is the mass fraction of specie *i*, and *T* is the temperature of the flow (K). CFD can simulate this process and visualization of the movement as shown in **Figures 8–10**.

The discretization of components in semi-closed facilities can better depict fluxes under different scenarios. **Figure 8** shows the air movement along the barn and how the temperature is changing. In addition, air exchange promotes an efficient distribution of gas concentration by the effect of ventilation system.

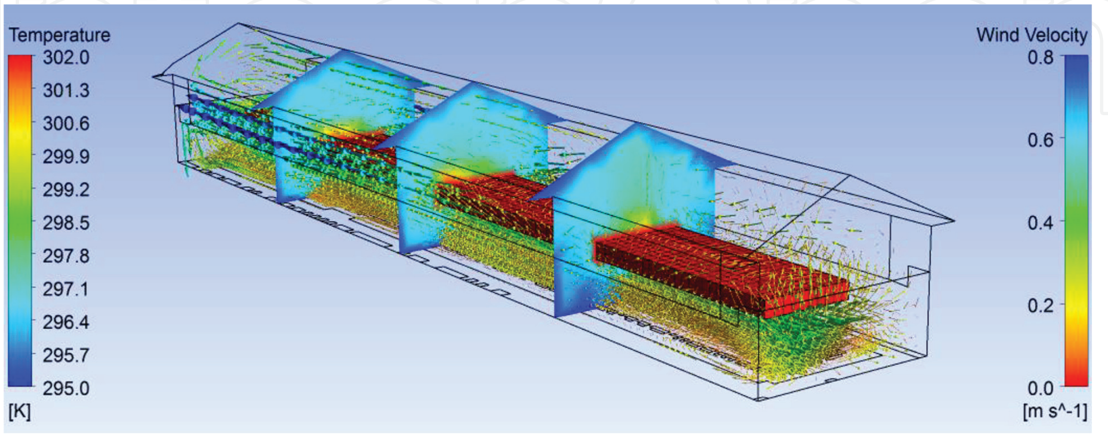

Figure 8.
Wind velocity vectors (m s⁻¹) under cages and surrounding temperature profiles (°C).

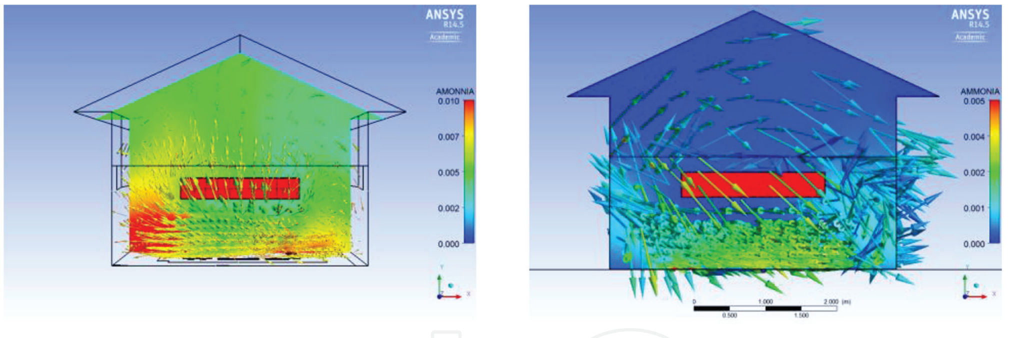

Figure 9.
Relative gas concentration by air exchange effect.

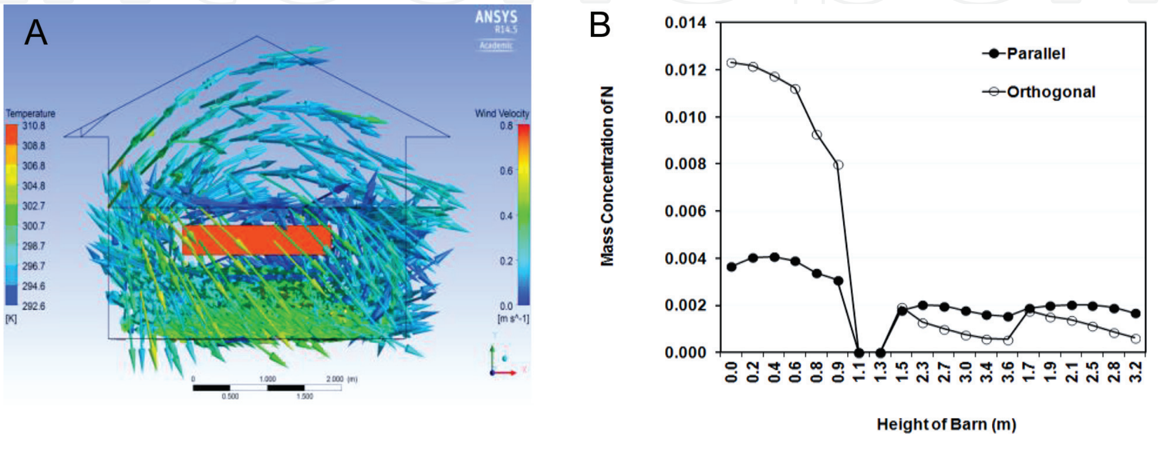

Figure 10.
CFD results of (A) profile of wind velocity and temperature and (B) relative gas concentration of nitrogen in a vertical profile, under two wind direction configurations (cages are in the 1.1 m height).

Performance of the vents is a function of their size, position, and proportion to the whole ground area.

In this study mass and energy transfer was revised to get reduced the negative effect of the ammonia gas in the rabbit barn development. Two climatic variables are responsible to the rabbit's health: temperature and humidity. Both climate variables were got better when the position of windows was changed. These results are consistent with CFD simulations, where the effective renovation rate depends on the position of the window. In some cases more than 50% of the air cannot get in through the inlet vent, producing a ventilation rate of 5.4 kg s^{-1}. As a consequence, a greater dispersion of toxic gases and lower temperature gradients (5 K) are produced.

The air exchange rate is an indicator of gas movement, because it is similar for both the air and the gas being simulated such as the ammonia (**Figure 9**) with a wind direction normal to the ridge. When the wind is parallel to the vents, the air that enters the vents by pressure difference produces a higher ventilation rate at the zone beneath the cages (**Figure 10**), even when the ventilation rate is close to zero. In contrast, when the wind flows normal to the ridge, ventilation rates increase.

Numerical models show a representative environmental dynamics, which can supply information for manage and control of several climate factors.

Continuity equation indicates that mass quantity entrance must be the mass in exit; however, with the change in the configuration of orientation of barn, the gas concentration can be better. Using CFD simulation, the concentration of gas under/over cages is calculated. **Figure 10** shows the mass transfer due to natural ventilation systems and the wind direction with respect to the size of the windows. In this case the position of the size of the windows was enough to reduce the mass transference under cages. Results indicated that the rate of mass change is the same, but distribution of gases (mass exchange) can be managed using different configuration of windows.

5. Conclusions

Numerical tools applied at predictive models of heat and mass transfer are helpful to better manage water-climate-soil inputs to plants in greenhouses. Computational fluid dynamics models are used to describe the greenhouse microclimate and the behavior of the plant-environment interaction in greenhouses. CFD is a powerful tool, to get the analysis of interactions between components of biosystem. Cover material, soil, and crop with other components must be included in the model. The crop can be considered as a porous medium and measured transpiration and sensible heat transfers. CFD models and auxiliary programming tools have been widely used to measure the interactions between the mass and energy transfer processes within the greenhouse and other biosystems, with excellent results.

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