Considering plant activities in greenhouse climate models using computational fluid dynamics: current achievements and future perspectives

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Abstract

Since the 1990s, Computational fluid dynamics (CFD) modeling has made significant advancements in studying greenhouse climates. The precision and effectiveness of these models largely depend on their capability to accurately replicate the dynamic interactions between crops and airflow, particularly the exchange of heat and mass. Integrating plant activities into CFD-based greenhouse climate models enhances precision in simulating conditions inside the greenhouse and within crops. This multi-scale approach ranges from the entire greenhouse to individual plant leaves, achieving high precision down to a few cubic centimeters. The model considers air-crop interactions using porous media to represent crop rows, facilitating the exchange of momentum, heat, and mass with the air. Specific terms for momentum, heat fluxes, and mass exchanges are assigned to each cell of the porous medium, incorporated into a user defined function (UDF) that acts as a crop submodel linked to the main CFD solver. By simultaneously solving the conservation equations, the radiative transfer equation, and the crop submodel equations, the CFD model can directly simulate the local distributions of air velocity, temperature, humidity, and radiation within the greenhouse and in the crop rows. These climate distributions enable the indirect estimation of variables such as CO2 distribution within the crop rows together with plant activity parameters such as transpiration and photosynthesis. Still, to further improve the accuracy and applicability of the CFD models in greenhouses, advancements are needed in plant representation, plant-environment interaction, and multiscale modeling. A better understanding of radiation transfers within crop stands, the development of virtual plants under CFD models, and the integration of other biotic

and non-biotic interactions will contribute to more effective greenhouse design and management.

Keywords: CFD modeling, crop model, transpiration, photosynthesis, climate control

INTRODUCTION

Computational fluid dynamics (CFD) is a branch of fluid mechanics that uses numerical analysis and data structures to solve and analyze problems related to fluid flows. It has various applications in fields such as meteorology, automobile industry, aeronautics, and more. In recent years, CFD has been increasingly used in agriculture, particularly greenhouse environments.

Early studies in greenhouse CFD modeling focused on optimizing ventilation and structure design, without considering the impact of the crop on airflow and the microclimate inside the greenhouse (Okushima et al., 1989; Mistriotis et al., 1997a, b, c). However, advancements have been made in modeling the distributed microclimate within greenhouses, considering the dynamic effects of the crop on airflow, heat, and mass exchanges. Researchers have customized commercial CFD software to include drag and transpiration activities of plants, enabling simulations of crop-specific processes (Haxaire, 1999; Boulard and Wang, 2002; Fatnassi et al., 2003, 2006, 2015; Majdoubi et al., 2009, 2016; Kichah et al., 2012; Boulard et al., 2017; Tadj et al., 2017; Bouhoun Ali et al., 2018, 2019; Baxevanou et al., 2020; Ben Amara et al., 2021; Cheng et al., 2021; Liu et al., 2020).

Studies have also explored the photosynthetic activity of crops using CFD. Models have been developed to simulate photosynthesis based on factors such as light and CO2 concentration. These models have been validated through comparisons with experimental measurements (Reichrath and Davies, 2001; Roy et al., 2014; Boulard et al., 2017).

Additionally, to apply CFD-based modeling approaches to integrated crop protection, particularly for controlling the development of insect pests and plant diseases, researchers have incorporated microclimate modeling within the leaf boundary layer, which represents the ecological niche of plant pests (Boulard et al., 2002; Bresch et al., 2019; Fatnassi et al., 2021).

Besides modeling the climate, energy, and matter exchanges in the greenhouse and the leaf boundary layer, other approaches have been developed through CFD numerical simulation of biotic particle transfers. This enhances our understanding of the origin of pathogen inoculum. Thus, the comprehensive greenhouse model, which already includes momentum (air velocity), heat (temperature), and water vapor (water vapor pressure) transfers, has been extended to incorporate spore transfer (spore concentration). They adopted an Eulerian approach, compatible with the global climate model considered in the CFD approach (Boulard et al., 2008; Leyronas et al., 2011; Fatnassi et al., 2015, 2021).

Different types of greenhouses, including multispan plastic houses, large greenhouse tunnels, and Chinese solar greenhouses, have been investigated using CFD simulations coupled with climate characterization studies (Haxaire, 1999; Boulard and Wang, 2002; Fatnassi et al., 2003; Majdoubi et al., 2009; Zhang et al., 2016; Tong et al., 2018; Jiao et al., 2020; Liu et al., 2020; Wu et al., 2021). The results have demonstrated a good fit between measured and simulated values, providing confidence in the accuracy of these coupled numerical models.

While the porous medium approach, treating the canopy as a porous medium, is commonly used in crop-cover transfers, other approaches have been explored. Some models consider the exact form of leaves, plants, and stomata. For instance, innovative

approaches have integrated stomatal and leaf-scale modeling within a comprehensive computational model.
This paper summarizes the existing literature on integrating plant activities into CFD climate modeling. It discusses the implementation of dynamic interactions, heat, and mass exchanges between the plant and its environment within a two-loop numerical model. The paper provides detailed instructions for implementing these plant activities in CFD modeling and presents the main results obtained from simulations using a crop submodel.

DESCRIPTION OF THE CFD NUMERICAL MODEL

The model developed incorporates multiple scales of modeling to represent the various components of the greenhouse. The primary model focuses on airflow, heat, and mass transfer within the greenhouse and its surroundings, utilizing the Navier-Stokes and energy equations:

$\partial(U\Phi)\partial X+\partial(V\Phi)\partial Y+\partial(W\Phi)\partial Z=\Gamma\Phi.\nabla 2\Phi+S\Phi$ (1)

where Φ represents the concentration of the transported quantity expressed in a dimensionless form (mass, momentum, energy); U, V, and W are the components of the velocity vector in m s-1, $\Gamma\Phi$ is the diffusion coefficient of the transported variable; and $S\Phi$corresponds to source (or sink) terms.
Additionally, a crop model is integrated into the main computational fluid dynamics (CFD) model to simulate airflow and mass exchanges within the crop cover, treated as a porous medium.
This approach accounts for two significant phenomena:

The dynamic effect of the crop cover on air flow Sc expressed by unit volume of the cover by the commonly used formula (Fatnassi et al., 2006):
$Sc=-LADCd\rho u2$ (2)
where u is the air speed within the crop cover in m s-1, LAD is the leaf area density in m2 s-3 and Cd is a drag coefficient, dimensionless.
In order to include the drag effect proportional to the leaf density into the CFD model, the crop cover can be considered as a porous medium using the Darcy-Forsheimer equation:

$Sc=-((\mu K/)u+(CFK0.5/)u2)$ (3)

where μ is the dynamic viscosity of the fluid in kg s-1 m-1, K is the permeability of the porous medium in m2 and CF the nonlinear momentum loss coefficient, dimensionless. For the low air speed values observed into the crop cover, the first term of Equation 3 can be neglected in front of the quadratic term. Combining then Equations 2 and 3 yields:

$CFK0.5/=LADCD$ (4)

The exchanges of heat and water vapor between leaves and air are described by means of the heat and mass balances of leaves with the air (Figure 1). Each mesh of the crop cover is assimilated to a "volume heat source boundary condition" receiving a radiative flux, $Gabs$. This flux is partitioned into convective sensible (Ss) and latent (SL) heat fluxes (water vapor) according to the relations:

Gabs=SS+SL (5)
$SS=LAD\rho CP(Tl-Ta)ra/$ (6)

$SL = \gamma LAD \rho CP (ql* - qa)(ra/+rs)$ (7)

where rs and ra are the stomatal and aerodynamic resistances (in s m-1) between the virtual solid matrix representing the crop and characterized by its surface temperature Tl and the air Ta in °C; $ql*$ and qa are the saturation specific humidity at the leaf temperature and the specific humidity of air respectively in kg kg^{-1}.

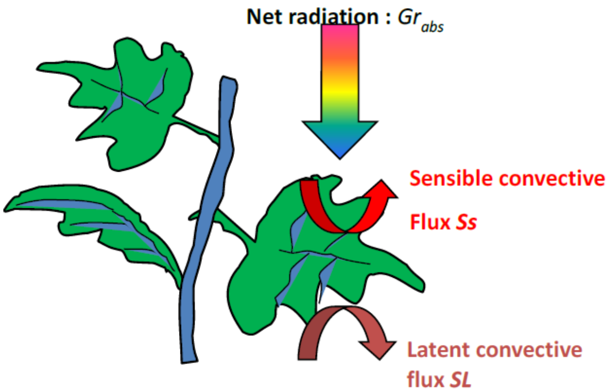

Figure 1. Net radiation, sensible and latent heat balances of leaves.

Both couplings have already been amply studied and published in various studies performed in greenhouse conditions for lettuce crops (Boulard and Wang, 2002); rose crops (Fatnassi et al., 2006); single beans leaf (Roy et al., 2008); tomato crops (Fatnassi et al., 2003; Majdoubi et al., 2009); impatiens crops (Kichah et al., 2012) and the objective is also to explore the microclimate inside the leaf boundary layer using an analytical model derived of the boundary layer theory (Fatnassi et al., 2021).

CO2 EXCHANGE BETWEEN PLANTS AND AIR

CO2 exchange between plants and air occurs by photosynthesis and respiration process through stomata of leaves. Roy et al. (2014) used a used defined function (UDF) to simulate the absorption or production of CO2 produced by plants in a semi-closed greenhouse with a tomato crop and CO2 supply. They used a 3D model of a cropped greenhouse, including a discrete CO2 injection system and an air-cooling and dehumidifying system. They compared the simulated and measured CO2 concentration inside the greenhouse for a whole day and found that CFD simulations correctly predicted the time course for net CO2 consumption per greenhouse surface unit. The photosynthesis process is a high-interest topic that deserves more attention in the coming years.

Several expressions of the process are available, including Reichrath and Davies (2001), , Roy et al. (2014), Molina-Aiz et al. (2017) and Boulard et al. (2017).

Roy et al. (2014) and Boulard et al. (2017) used Thornley's (1976) model to simulate CO2 absorption in a semi-closed greenhouse with a tomato crop:

$Pr = ((\alpha I \tau \rho Ca \alpha I)/(\tau \rho Ca))LAD$ (8)

where α is the photosynthesis efficiency ($\alpha = 1.01\times10^{-10}$ kg CO2 J^{-1}); I ($W\ m^{-2}$) is the photosynthetically active radiation (PAR) incident radiative flux, τ the leaf conductance to CO2 transfer in $m\ s^{-1}$ (1/(ra+rs)), and Ca is the concentration of CO2 in surrounding air after unit conversion ($kg\ m^{-3}$).
The production of CO2 consists of maintenance and growth respirations, which together can be estimated for tomato crops to 22% of the raw photosynthesis consumption, hence the net photosynthesis consumption flux *SCO2* can be estimated as:

SCO2 = 0.78 Pr (9)

MILESTONES OF CFD CROP MODEL DEVELOPMENTS

Figure 2 illustrates the key milestones in the development of crop models. The initial research focused on incorporating the effects of crops on airflow using the porous medium approach. Subsequent efforts tackled the radiative transfer equation and calculated the distribution of global radiation within crop rows. Progressing from these foundational studies, later developments integrated various plant activities into the computational fluid dynamics (CFD) model. Notable among these activities are photosynthesis, water vapor exchange, and other critical parameters influencing the greenhouse environment.

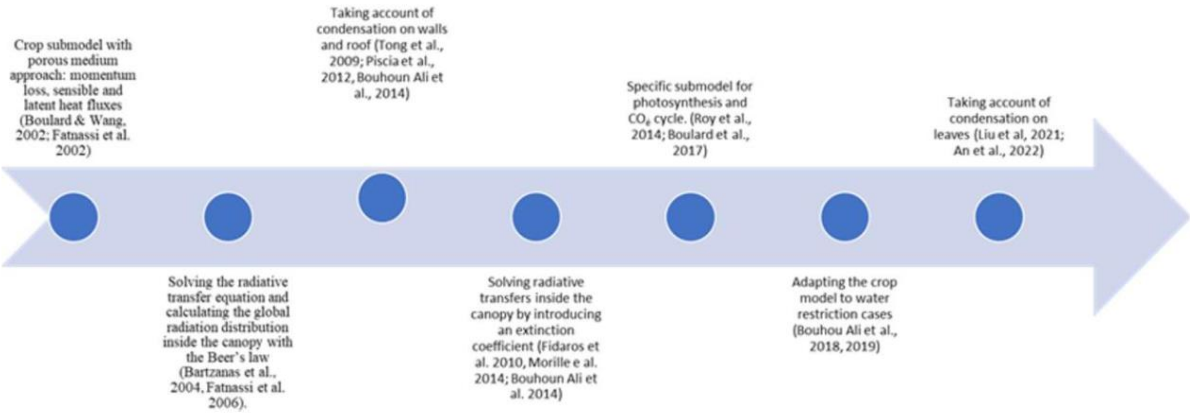

Figure 2. Milestones of CFD crop submodel developments.

DETAILED MICROCLIMATE ANALYSIS

The developed CFD model enables detailed analysis of spatial microclimatic variations within greenhouses, providing insights into temperature, humidity and air velocity distributions. By integrating convective, mass and radiative transfers within the crop rows, this model has been extended to include the interactions between plant activities and air inside the greenhouse. This enhancement provides detailed information on the distribution of plant leaf temperatures and CO2 concentration gradients influenced by plant processes.
The pioneering work of Boulard and Wang (2002) introduced crop representation in CFD models, encompassing mechanical interactions such as drag force, along with heat and water vapor transfers, particularly focusing on lettuce. Subsequently, Fatnassi et al. (2003, 2015), Fidaros et al. (2010), and Majdoubi et al. (2009, 2016) adapted this approach to tomatoes. Additionally, studies by Fatnassi et al. (2006), Kichah et al. (2012),

and Bouhoun Ali et al. (2018) explored ornamental plant interactions, including roses and New Guinea Impatiens. Chen et al. (2015) extended this investigation to begonia.
Recent advancements have focused on enhancing the crop submodel, particularly in modeling radiation distribution within the canopy itself, as demonstrated by Morille et al. (2013) and Bouhoun Ali et al. (2018).
Using this CFD modeling allowed for accurate mapping of the spatially distributed climate within various types of greenhouses worldwide (e.g., the multi-span greenhouse, as shown in Figure 3).

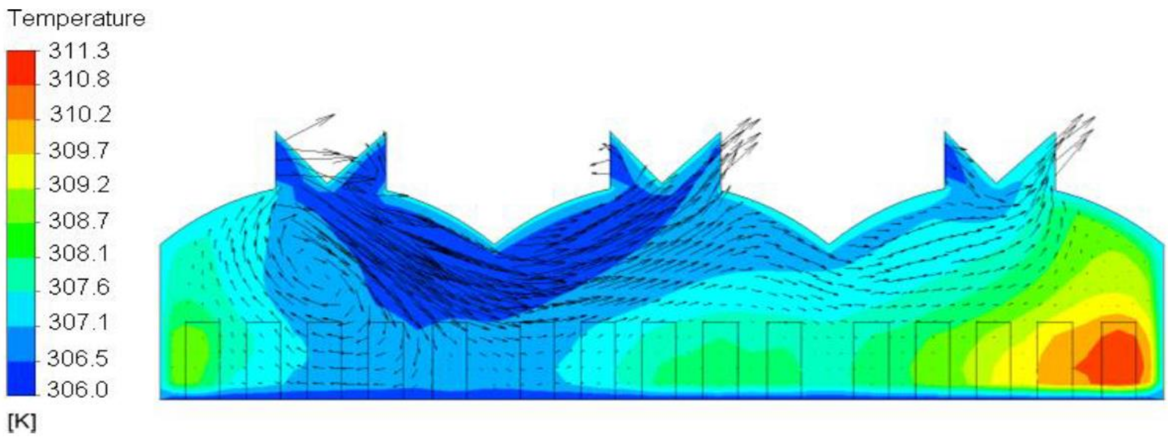

Figure 3. Airflow pattern and air temperature distribution inside a multispan greenhouse (Fatnassi et al., 2017).

Pouillard et al. (2012) considered an experimental closed energy saving greenhouse with a tomato crop. To assess the radiation distribution inside the greenhouse, they solved the radiative transfer equation, using the Discrete Ordinate model and distinguishing short from long wave radiations. Implementing a crop submodel encapsulated in a UDF dynamically linked with the main solver, they simulated the distribution of leaf temperature, air temperature and crop transpiration within the crop based on air velocity and surrounding climate parameters (Figure 4).
Their results evidenced that the heterogeneity of the climatic parameters inside the greenhouse strongly affects plant activity as illustrated in Figure 4 showing the distributions of leaf temperature, crop transpiration and short waves radiations received within the crop. Pouillard et al. (2012) also showed that for this greenhouse, 2/3 of the captured radiative energy was transferred to latent heat thus increasing air humidity while only the remaining part contributed to greenhouse air warm up and heat accumulation just below the roof.
Bournet et al. (2017) carried out two-dimensional unsteady simulations at a daily timescale including crop interaction, sun path and ground conduction. Here also, the Radiative Transfer Equation was solved based on the Discrete Ordinates method both for short and long wavelength radiations. The ground was also meshed to simulate conduction. The model was run for a typical sunny day under temperate climatic conditions and validation was undertaken based on seven different parameters including temperature and relative humidity of the air above and inside the crop, ground temperature, leaf temperature and transpiration rate (Figure 5).

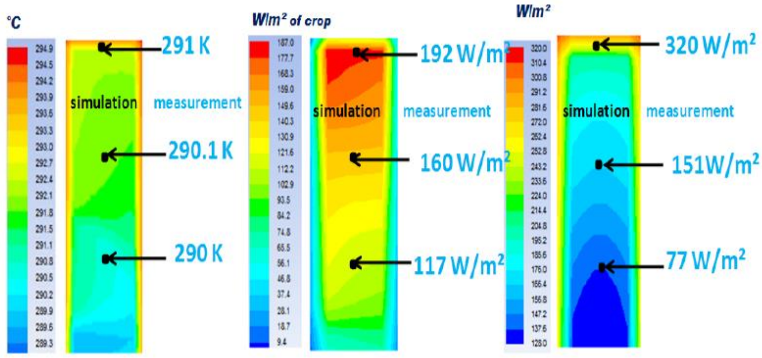

Figure 4. Simulated and measured (number in bleu characters) distributions of leaf temperature (left), crop transpiration (middle) and short waves radiations (right) within the crop cover (Pouillard et al., 2012).

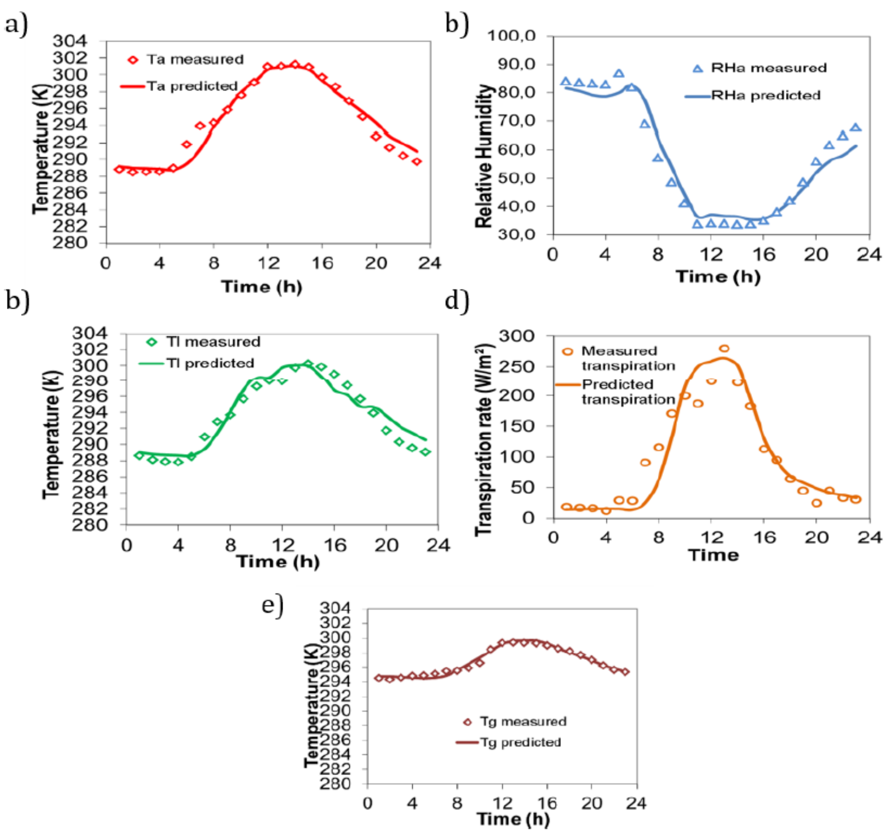

Figure 5. Comparison of measurements and CFD simulations for air temperature above the crop (a), relative humidity above the crop (b), leaf temperature (c), transpiration rate (d) and soil surface temperature (e) (adapted from Bournet et al., 2017).

Simulations stress the ability of the model to correctly predict the response of the greenhouse to a variation of the outside climate. In particular, the strong influence of the solar radiation was demonstrated. Although leaf temperature and transpiration rate were satisfactorily simulated, local air humidity and temperature inside the canopy were not so well predicted and differences with the above air characteristics were smoothed. They suspected that air movement inside the canopy could be overestimated due perhaps to an underestimation of the drag force of the porous medium.

Bouhoun Ali et al. (2018) adapted the crop model for cases when plants are subject to water restriction. To reach this goal, they defined a multiplicative term in the stomatal resistance expression as a function of the soil water potential. Coefficients appearing in this term were established from a fit over available stomatal resistance measurements (Cannavo et al., 2016). In addition, Bouhoun Ali et al. (2018) developed a submodel to calculate the water balance over the substrate. Considering in a first stage only a relatively small calculation domain around the plants, they first validated their model for well-watered plants and for plants under water restriction (i.e. irrigation was stopped). In particular, the model showed its ability to predict the decrease in the amount of water available in the substrate. As expected, simulations also showed that the stomatal resistance, the air temperatures inside the canopy and the leaf temperatures were higher for the water restriction conditions than for the well-watered case. In agreement with measurements, simulations also revealed that transpiration rates were lower for plants under water restriction than for plants under well-watered conditions (Figure 6).

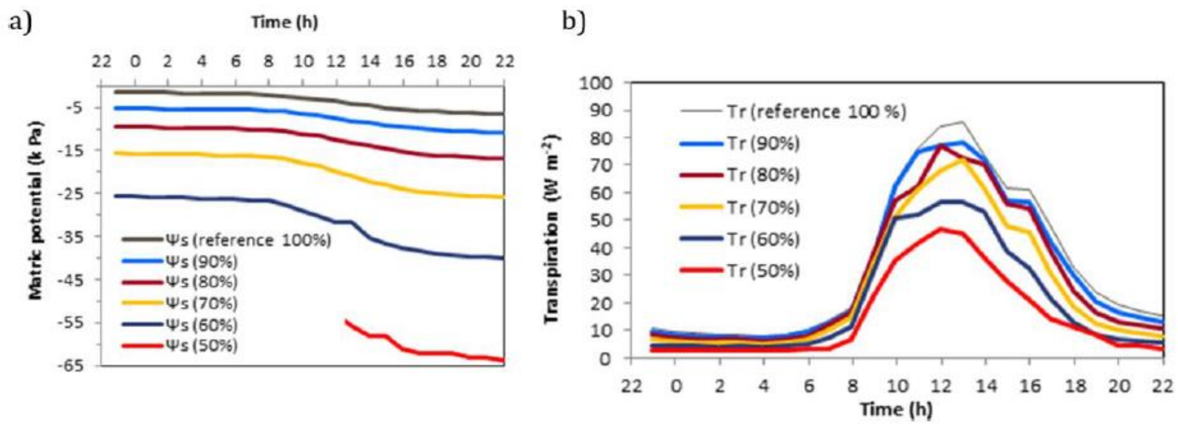

Figure 6. Evolution of the matric potential evolution in the ground (a) and corresponding evolution of the evapotranspiration predicted by a CFD model for an impatiens crop (b) (after Bouhoun Ali et al., 2018).

Indeed, suboptimal water inputs that may lead to stomatal partial closing and transpiration rate reductions, as is often the case in real situations. In order to identify an adapted strategy to decrease the amount of water supply with as little impact as possible on the transpiration and microclimate inside the greenhouse, six water irrigation regimes were then tested, ranging from well-watered conditions (saturation of the substrate), to half the water inputs corresponding to well-watered conditions. As expected, the growing media matric potential decreased with the reduction of water supply, causing an increase in the stomatal resistance that, itself, reduced the transpiration activity of the plants.

The same model was then implemented by Bouhoun Ali et al. (2019), but at the scale of the greenhouse itself. Six irrigation regimes were tested for the same conditions as the previous study. The same trends as those simulated for the first study (Bouhoun Ali et al., 2018) were reported. To avoid stomatal closure (which would reduce photosynthesis activity) and maintain transpiration activity, the authors point out the fact that the leaf temperatures should remain close to the adjacent air temperatures during the day. From that point of view, they conclude that the scenario with 70% water supply appears to be a good compromise. Moreover, using 70% of water instead of 100% makes it possible to save 0.19 L per container and per day. In addition to spare water, another advantage of reducing water supply is that it contributes to decrease humidity and therefore risks of fungal diseases or mold development. The CFD simulations could hence be helpful to improve water management strategy, making it possible to preserve the microclimate conditions adapted to plant development while reducing water inputs. It should be stated however that the authors did not investigate the impact of water restriction on plant architecture which is an important point to check to warranty the plant quality remains in agreement with the marketing criteria.

SIMULATION OF DISTRIBUTION OF CO2 CONCENTRATION IN THE GREENHOUSE

The carbon dioxide behavior associated with the photosynthesis and respiration processes was also considered in the CFD model. This has allowed mapping the CO2 concentration, together with temperature and water vapor concentration inside a cropped greenhouse equipped with a CO2 injection system.

Reichrath and Davies (2001) were to our knowledge the first to be interested in including the crop's total carbon dioxide uptake rate for photosynthesis in CFD modeling. They followed Acock's suggestion and divided the crop into three layers. The top layer of the crop consumes 66% of total carbon dioxide, the middle layer 27%, and the bottom layer 7%.

The carbon dioxide injection through the layflats and carbon dioxide absorption by the crops were added to the two-dimensional CFD model that was applied to a 60-span venlo type glasshouse. Carbon dioxide dispersion was simulated, and it revealed a high concentration in the leeward part of the glasshouse due to less efficient ventilation compared to the windward side of the house (Figure 7).

Figure 7. Carbon dioxide dispersion in a 60 span Venlo-type glasshouse with crops (Reichrath and Davies, 2001).

On the other hand, Roy et al. (2014) investigated the CO2 distribution in a closed plastic-greenhouse using both numerical and experimental approaches, including a CFD model and direct measurements. In contrast to Reichrath and Davies (2001), Roy et al. (2014) used a 3-dimensional CFD model. In their study, the CO2 concentration was solved by adding a transport equation for the CO2 mass fraction in the 3-D CFD model, and the photosynthesis flux was considered as a function of this concentration.

The results disclose the distribution of CO2 concentrations in the greenhouse at various times of the day. For example, at 9:00 am the greenhouse is closed, and the CO2 supply is turned on, which corresponds to the seven high CO2 concentration zones that appear near the ground (Figure 8a). CO2 levels are high at the bottom of crop rows (1,200 ppm) and fall to 1,000 ppm at the top. At 11:00 am, the greenhouse is still closed, and the CO2 supply is turned off, and the stratification of CO2 concentration is shown, with lower values: 10:00 ppm at the bottom and 8:00 ppm at the top of crop rows, due to higher radiation flux at these levels (Figure 8b).

Molina-Aiz et al. (2017) used the same approach as Roy et al. (2014) and created a CFD model to simulate photosynthesis in an *Almeria*-type greenhouse by incorporating the Acock model in a UDF. The CFD simulation results were compared to the experimental data, and good 145

agreement was found. CO2 concentrations ranged from 410 ppm in the greenhouse's center to 373 ppm inside the tomato canopy. The photosynthesis rates measured in the crops ranged from 10.3 to 16.8 μmol CO2 m^{-2} s^{-1}.

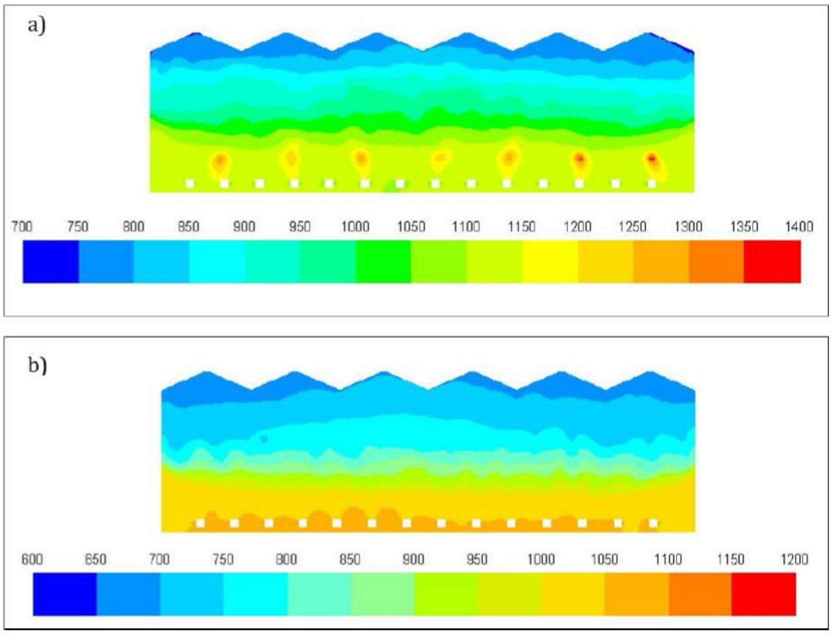

Figure 8. CO2 rates (ppm) in a median transverse plane of the greenhouse at 9:00 am (a) and 11:00 am (b) (Roy et al., 2014).

The CO2 distribution results also show a decrease in concentration in the leeward part of the greenhouse, where plants absorb CO2 through photosynthesis (Figure 9). The concentration of CO2 in the windward part of the greenhouse was similar to the outside value, indicating that natural ventilation was sufficient to maintain an adequate concentration for the plants.

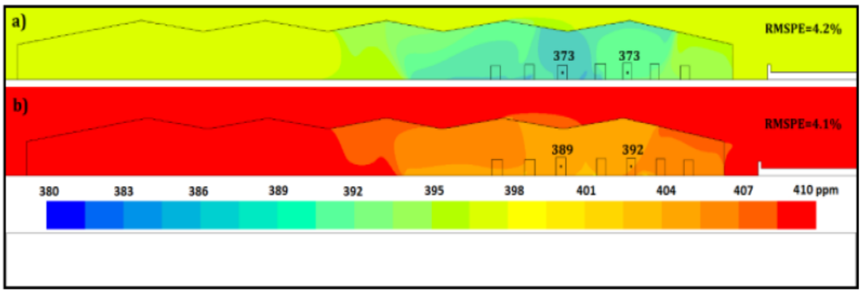

Figure 9. Distributions of CO2 concentration simulated with CFD and measured values (figures) in the greenhouse on 3/11/2014 (a) and on 3/13/2014 (c) (Molina-Aiz et al., 2017).

FUTURE TRENDS

Despite advances in CFD-based plant activity modeling in greenhouses, further improvements are necessary to achieve greater realism. Enhancements are needed in areas such as radiation transfer, light distribution validation, virtual plant development, and biotic/non-biotic interactions. Current simulations must account for various light qualities, including those from the sky, greenhouse cladding, structural elements, shelves, and canopy. Advancements in computer facilities and model development present opportunities to enhance radiation considerations in CFD modeling tools. Virtual plants can be developed by creating 3D models of plants, calculating photosynthesis and transpiration at the leaf level, and considering microclimate and transport-resistance systems. Additionally, further development is required for pest control management, early warning models for diseases, and real-time application of CFD tools in greenhouse production.

CONCLUSIONS

This paper provides a detailed explanation of the various steps involved in integrating greenhouse plant activity into computational fluid dynamics (CFD) models. Specifically, it focuses on the sub-program that calculates the relevant parameters and establishes connections with the main solver.

Since the 1990s, numerous CFD models have been developed to couple the dynamic effects and mass exchanges between crops and the air within greenhouses. These models have undergone systematic validations, demonstrating their accurate prediction of air velocity, temperature, humidity, and CO2 distribution within the greenhouse, including the crop rows or canopy. Furthermore, they offer valuable insights into plant activity, often encompassing transpiration and occasionally photosynthesis. They also enable testing and refinement of greenhouse design and equipment to enhance crop production. However, despite these advancements, there is still room for further improvement in enhancing the precision and suitability of CFD models for greenhouse applications. Progress is needed in the areas of plant representation, plant-environment interaction, and multiscale modeling. Improving our understanding of radiation transfers within crop stands, incorporating virtual plants into CFD models, and integrating additional biotic and non-biotic interactions will contribute to the development of more efficient greenhouse designs and management strategies.

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