Computational fluid dynamics modelling of the indoor environment of a small-scale high-density controlled environment agriculture (CEA-HD) space

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Abstract

This paper investigates the modelling of the indoor environment of a small-scale high-density controlled environment agriculture (CEA-HD) space with user defined functions (UDFs) specified in a computational fluid dynamics (CFD) commercial software. The indoor air speed, temperature, humidity and carbon dioxide fields were computed for a two-dimensional model of a CEA-HD space where the crops being grown were represented as porous media. The model showed consistent results with grid size and was used to assess the distribution of the different computed fields. Furthermore, a parametric analysis investigated the influence of inlet air speed on the predicted production space homogeneity, quantified using the coefficient of variation of the computed fields. The model identified possible problematic locations in the production space and identified an inlet configuration yielding a coefficient of variation of 44.2% over the computed air speed. The developed model, once validated, will support the development of enhanced designs and load calculation approaches for CEA-HD spaces.

Introduction

High-density controlled environment agriculture (CEA-HD) spaces are spaces where crops are grown indoor, under artificial lighting, using multi-tiered hydroponic cultivation systems. The crops are thus protected from meteorological variations, pests and other stress factors while being grown in a precisely controlled indoor environment, promoting growth and resource use efficiency. The control of the indoor environment in CEA leads to higher yield than agriculture in fields: the mass of crops harvested in a CEA-HD can be fifteen times higher than in greenhouses and a hundred times higher than in the field (Kozai et al., 2015).

This higher yield is possible by maintaining specific indoor environmental conditions: the indoor air (1) temperature, (2) humidity, (3) speed (4) carbon dioxide concentration and (5) the photosynthetically active radiation (PAR), all of which influence plant growth (Okayama et al., 2008). The PAR is provided using light emitting diodes (LEDs) with crop specific optimised spectrum and photoperiod. The other environmental conditions are maintained within an optimal range using Heating, Ventilation and Air Conditioning (HVAC) equipment. The proper design and operation of the HVAC equipment in CEA-HD spaces is currently challenging and the information available is sparse since most of the knowledge is proprietary (Jonlin & Lewellen, 2017). Still, in recent years, there has been several advancements made in this field.

For example, the loads and energy consumption of a CEA-HD space using the «*perfectly stirred tank*» hypothesis was assessed by Graamans et al. (2017). This assumes that the air inside the space is perfectly mixed and that the indoor environment conditions are homogenous. While this assumption can be used to size equipment and evaluate energy consumption or the mean indoor environmental conditions, it does not support the representation of the spatial distribution around the crops.

Maintaining the indoor environment spatial uniformity is challenging in CEA-HD spaces (Baek et al., 2015; Lim & Kim, 2014). The number of cultivation shelves, the increased resistance to airflow by crops and the heat generated by the artificial lighting can influence the indoor environment uniformity, which is essential to obtain a homogeneous crop production and prevent localized «*hot spots*» (Lim & Kim, 2014). Even with fans, local high temperature areas may exist in the cultivation zone (Jiang et al., 2018). High local humidity can also lead to fungus growth yielding production problems. Okayama et al. (2008) stated that improved airflow control could lead to energy savings while maintaining the quality of crops being grown. Often, in CEA-HD, distributed or centralised fans are used to ensure adequate air speed at the leaves and ensure uniformity of the indoor environmental conditions to enhance crops growth.

Computational fluid dynamics (CFD) is an effective tool yielding reasonable accuracy in modelling complex phenomena in controlled environments (Zhang & Kacira, 2018; Zhang et al., 2016). While CFD has been used to predict the airflow characteristics in CAE production spaces such as greenhouses, only a few studies have modelled air distribution in CEA-HD spaces using CFD. A review of CFD modelling in CEA spaces, including greenhouses is provided in Table 1. One of the identified short-coming is

that the humidity and the carbon dioxide fields were not modelled in the CFD software. Hence, the spatial distribution of those two field variables, influenced by the transpiration and photosynthesis of the crops, has not been assessed yet. Additionally, the effect of the crops on the airflow has also been neglected. Yet, several studies have highlighted the influence of vegetation on airflow (e.g., Koch et al. (2019)). This limitation has been recommended as future work by Zhang et al. (2016).

Okayama et al. (2008) investigated three airflow control patterns over a single lettuce cultivation shelves using a simplified geometry in a commercial CFD tool. They also estimated the effect of the airflow speed on the photosynthetic rate using a relationship extracted from results obtained by Kitaya et al. (2003). Lim and Kim (2014) modelled and validated the air flow distribution inside a small-scale CEA-HD and investigated four air distribution inlet-outlet combinations with their validated model to improve airflow distribution. Baek et al. (2016) studied different combinations of airflow equipment using CFD. They subsequently conducted growth experiments based on their CFD results and obtained improved yield. Zhang et al. (2016) investigated perforated tube air distribution system layouts inside a small CEA-HD space using CFD. The air flow uniformity in the CEA-HD space was evaluated using the coefficient of variation computed over the mesh cells at the top of the crop canopy. Zhang and Kacira (2018) evaluated the performance of five air distribution configurations varying inlet and outlet locations using the coefficient of variation (CV). They achieved a CV of 39.25% but could not reach the desired airflow of 3.0 m/s at the canopy. Niam et al. (2019) investigated the effect of two air conditioner locations in a plant factory built in a shipping container on the air temperature distribution. They reported high uniformity of carbon dioxide concentration but neglected to model the crops photosynthesis and airflow impingement.

Thus, none of the listed CEA-HD spaces modelling approaches in Table 1 simultaneous addressed crop airflow impingement, photosynthesis, and transpiration as well as radiation heat transfer. Hence there is a need, at the CEA-HD level, to propose a modelling approach that would included all of these phenomena. In this paper, CFD modelling of a small-scale high-density controlled environment agriculture (CEA-HD) space that considers the impact of crops in terms of airflow impingement, transpiration, and photosynthesis is performed. A parametric analysis is completed on the inlet boundary conditions to identify the theoretical inlet operational parameters that maximise airflow uniformity around the crops.

Methods

In order to predict the spatial indoor environment conditions inside a CEA-HD space, the fundamentals equations of computational fluid dynamics need to be solved. The effect of the crops on the computed air speed, temperature, humidity and carbon dioxide fields also needs to be considered. Modelling crops in CFD software is not a trivial task: so-called *«User Defined Functions (UDFs)»* need to be developed. While these UDFs can be adapted to most CFD codes, they were tailored, for the purpose of this study, to ANSYS Fluent R19.2.

The proposed approach consists in (1) solving the Reynolds averaged Navier-Stokes (RANS) equation using a commercial CFD code while (2) modelling the crop effects in the CFD software as a porous medium combined with custom *«User Defined Functions»*. Following the development of the model, it is verified using (3) grid convergence analysis and used to explore the impact of the inlet operational parameters on the spatial uniformity using (4) a parametric analysis.

Table 1. Identified references concerning CFD analysis in CEA spaces after 2008.

References	Geometry	Crops	Radiation	Turbulence model	Energy	Photosynthesis	Transpiration
Kim et al. (2008)	3D	-	DO	k-ε	✓	-	-
Piscia et al. (2011)	3D	-	-	k-ε	✓		✓
Kichah et al. (2012)	2D	✓	-	k-ε	✓	-	✓
Nebbali et al. (2012)	3D	✓	DO	k-ε	✓	-	✓
Roy et al. (2013)	3D	-	DO	k-ε	✓	✓	✓
Piscia et al. (2013)	3D	-	-	k-ε	✓	-	constant source
Farber et al. (2015)	3D	✓	DO	k-ε	✓	✓	✓
Benni et al. (2016)	2D	-	-	ml	✓	-	-
Farber et al. (2017)	3D	✓	DO	k-ε	✓	-	✓
Boulard et al. (2017)	3D	✓	DO	k-ε	✓	✓	✓
Saberian and Sajadiye (2019)	3D	✓	DO	k-ε	✓	-	-

DO : discrete ordinates radiation model, ml : mixing length turbulence model

Computational fluid dynamics (CFD)

The fundamental equations of fluid dynamics – the continuity equation (equation (1)), the conservation of momentum equation (equation (2)) and the conservation of energy equation (equation (3)) – need to be solved to predict the distributed indoor environment field variables inside the space.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{V}) = 0 \quad (1)$$

$$\frac{\partial (\rho \boldsymbol{V})}{\partial t} + \nabla \cdot (\rho \boldsymbol{V}\boldsymbol{V}) = -\nabla p + \nabla(\bar{\bar{\tau}}) + \rho \boldsymbol{g} + \boldsymbol{F} \quad (2)$$

$$\frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\boldsymbol{V}(\rho E + p)) = \nabla \cdot \left(k_{eff} \nabla \mathrm{T} - \sum_j h_j J_j + (\bar{\bar{\tau}}_{eff} \cdot \boldsymbol{V})\right) + S_h \quad (3)$$

Where ρ is the fluid density, $\boldsymbol{V}$ is the velocity vector, p is the pressure, $\bar{\bar{\tau}}$ is the stress tensor, $\boldsymbol{g}$ is the gravity vector, $\boldsymbol{F}$ is the external forces, k_{eff} is the effective conductivity, T is the temperature, h_j the enthalpy, J_j the diffusion flux, and S_h is the volumetric heat sources.

As most indoor flows are turbulent in nature, the turbulence of the airflow must be modelled with specific equations. The k-ε turbulence model is chosen based on the literature consulted both on greenhouses and CEA-HD spaces airflow modelling (Table 1). Indeed, almost all identified studies in CEA-HD spaces used this turbulence model. This is modelled according to equation (4) for the turbulence kinetic energy (k) and equation (5) for the dissipation of the turbulence kinetic energy (ε).

$$\frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho k \boldsymbol{V}) = \nabla \cdot \left[\frac{\mu_t}{\sigma_k} \nabla \mathrm{k}\right] + 2\mu_t E_{ij} E_{ij} - \rho \varepsilon \quad (4)$$

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho \varepsilon \boldsymbol{V}) = \nabla \cdot \left[\frac{\mu_t}{\sigma_\varepsilon} \nabla \varepsilon\right] + C_{1\varepsilon} \frac{\varepsilon}{k} 2\mu_t E_{ij} E_{ij} - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \quad (5)$$

Where μ_t is the turbulent viscosity, σ are the turbulent Prandtl numbers and $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are the model constants. The humidity and carbon dioxide transport are modelled using the species transport model described by equation (6).

$$\frac{\partial (\rho Y_i)}{\partial t} + \nabla \cdot (\rho \boldsymbol{V} Y_i) = -\nabla \cdot (\boldsymbol{J}_i) + R_i + S_i \quad (6)$$

Where Y_i is the local mass fraction, $\boldsymbol{J}_i$ the diffusive flux, R_i the net rate of production and S_i the species sources. For a turbulent flow, the diffusive flux is modelled as per equation (7)

$$\boldsymbol{J}_i = -\left(\rho D_{i,m} + \frac{\mu_t}{Sc_t}\right) \nabla Y_i - D_{T,i} \frac{\nabla T}{T} \quad (7)$$

Where Sc_t is the turbulent Schmidt number and D_T is the turbulent diffusivity. Equations 1 to 7 address continuity, momentum, energy, turbulence and mass transport, but do not consider the impact of crops. For this impact to be considered, a crop sub-model is proposed that is based on additional equations that are integrated as part of the developed CFD model of the CEA-HD space.

Crop sub-model

Crops inside a CAE space exchange mass, heat and momentum with the environment, which influence the modelled indoor environment conditions. Modelling of these exchanges is crop specific but often linked to the leaf area index (LAI) or the leaf area density (LAD). The LAI is defined by the total one sided leaf area per horizontal surface unit (Watson, 1947) and the LAD is defined as the LAI divided by the crop height.

In this paper, the cop sub-model is detailed for lettuce since it is frequently cultivated in CEA-HD space due to its short cultivation cycle and low light intensity requirements (Okayama et al., 2008). The crop sub-model includes equations to consider the impact of (1) crop airflow impingement, (2) crop transpiration and (3) crop photosynthesis.

Crop airflow impingement

Modelling a plant inside a plant canopy, including the individual leaves, is currently very challenging (Defraeye et al., 2013). As a compromise between accuracy and computational time, it is proposed to model the plant canopy as a porous media. This approach has been used extensively to model the effects of crops on the airflow in greenhouse (Boulard et al., 2017; Farber et al., 2017; Kichah et al., 2012; Nebbali et al., 2012) and in urban heat islands effect (Manickathan et al., 2018). Furthermore, Koch et al. (2019) experimentally validated the effect of different crops species inside a small wind tunnel. In this paper the formulation from Boulard et al. (2017) is used and adapted to represent the effect of the crops on the momentum as detailed in equation (8).

$$\boldsymbol{F}_{x,y} = -\rho \cdot C_d \cdot LAD \cdot U \cdot u_{x,y} \quad (8)$$

Where ρ is the air density, C_d is the drag coefficient of the canopy, U is the magnitude of the velocity vector and $u_{x,y}$ is the corresponding cartesian projected air speed.

Crop Transpiration

In enclosed hydroponic systems, evaporation of the nutritive solution can be assumed to be negligible (Monje (1998). Therefore, the only source of humidity into the CEA-HD space is the transpiration from the crops. Multiple transpiration models have been proposed, most of which are derived from an energy balance at the leaf (Talbot & Monfet, 2020). In this paper, the model proposed by Graamans et al. (2017) is used since it has been validated experimentally under steady-state conditions as part of a study of a controlled-environment agriculture (CEA) space (equation (9)).

$$R_n - H - LE = 0 \quad (9)$$

Where R_n is the short-wave radiation flux (PAR) absorbed by the crops from lights and is set to a constant in the proposed model, H is the convective exchange flux with the indoor air and LE is the latent exchange flux with indoor air. The convective exchange flux is computed using equation (10)

$$H = LAI \cdot \frac{\rho c_p}{r_a} (T_{leaf} - T_{air}) \quad (10)$$

Where r_a is the aerodynamic resistance, T_{leaf} is the leaf surface temperature, c_p is the air specific heat capacity and

T_{air} the indoor air temperature. The heat balance equation (equation (9)) is solved for the leaf temperature using the secant method (Kreyszig, 1999) in each cell of the porous media domain. The latent exchange flux is solved according to equation (11)

$$LE = LAI \cdot \frac{\rho c_p}{66\,(r_a + r_{sl})}\left(SP\left(T_{leaf}\right) - SP(T_{air}) \cdot RH\right) \quad (11)$$

Where r_{sl} is the stomatal resistance, SP is the saturation pressure function (ASHRAE, 2013) and RH is the air relative humidity. The aerodynamic resistance (r_a) is modelled using equation (12), while the stomatal resistance (r_{sl}) is modelled using equation (13), (14) and (15).

$$r_a = 305 \cdot \frac{0.15}{\sqrt{\|V\| + \left(9.81 \cdot 0.0034 \cdot |T_{leaf} - T_{air}|\right)^{0.5}}} \quad (12)$$

$$r_{sl} = 120 \cdot f_1 \cdot f_2 \quad (13)$$

$$f_1 = 1 + e^{0.043 \cdot (R_n - 49)^{-1}} \quad (14)$$

$$f_2 = 1 + e^{0.043 \cdot (T_{leaf} - 0.38)} \quad (15)$$

Crop Photosynthesis

Corp photosynthesis is modelled to assess the carbon dioxide distribution within the space. Carbon dioxide is essential to the growth of crops via the Calvin cycle and photosynthesis. In the CEA-HD, the carbon dioxide concentration is usually maintained around 1000 – 1200 ppm using an injection system to promote crop growth. Only one photosynthesis equation (equation (16)) applied to the CFD analysis of the airflow in CEA-HD was found, which was proposed by Okayama et al. (2008) based on the results of Kitaya et al. (2003), but not experimentally validated.

$$P_{cell} = 1.4 \cdot (1 - e^{-12.8s}) + 1.52 \quad (16)$$

Where P_{cell} is the cell net photosynthetic rate and s is the air speed. Equation (16), currently used in the model, is a simplified representation of a complex process and might require further development.

Model description

The geometry of the experimental small-scale CEA-HD space is first modelled in a commercial CAD software (Solidworks). Figure 1 illustrates the 3D models of the production system and of the enclosure.

From the 3D model, a plane section model (2D) is extracted from the geometry (blue plane in Figure 1 (b)) and used as an input in the CFD software ANSYS Fluent (R19.2). A mesh is then generated prior to solving the previously stated equations as illustrated in Figure 2. The inlet boundary conditions and the parameters used to model the effects of the crops on the airflow are listed in Table 1.

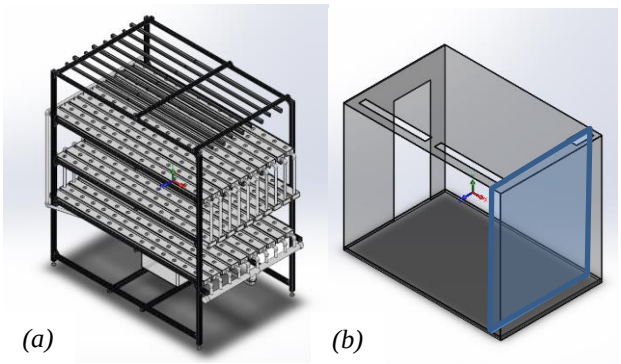

Figure 1 : 3D models of (a) the production system and (b) the enclosure of the small-scale CEA-HD space with the simulation plane (blue).

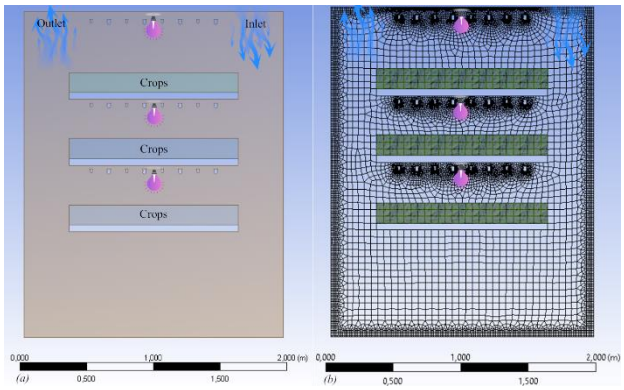

Figure 2 : Small-scale CEA-HD space (a) 2D geometry (left) and (b) 2D mesh generated in ANSYS (right)

Table 1: Inlet boundary conditions and crops modelled values

Location	Parameter	Value
Inlet	Temperature	15ºC
	Relative humidity	20%
	CO_2 concentration	400 ppm
	Air speed	0.5 m/s
Crop	LAI	1
	LAD	2.4
	Net radiation (R_n)	120 W/m²

Results

Solving the equations yielded the predicted field variables inside the modelled small-scale CEA-HD space. To ensure that the results are grid independent, a grid convergence analysis is first completed. The input parameters used for this analysis are the cell size input for the meshing program. The observed outputs are the average relative humidity and average air speed inside the porous media on the lower growing rack, which is one of the regions of interest of the simulation. Figure 3 presents the results of a grid convergence analysis showing that the grid sizes used fall within the asymptotic region of the chosen integral quantities of interest.

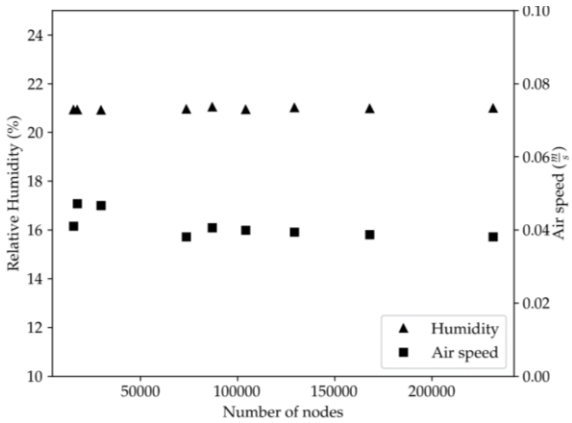

Figure 3 Grid convergence results for the lower growing rack porous media for the average humidity and air speed.

Additionally, manual inspection of the air speed, relative humidity, temperature and carbon dioxide contour plots exhibited the same flow characteristic, independent of the input grid size.

The results are presented for the finest grid size using contours plots for the air speed (Figure 4a), the temperature (Figure 4b), the relative humidity (Figure 4c) and the carbon dioxide concentration (Figure 4d). Figure 4a clearly shows that the majority of the predicted airflow is not directed towards the cultivated crops, but is diverted towards the side walls (consistent with the Coanda effect) and then passes under the cultivation rack before reaching the outlet. The temperature contour plot (Figure 4b) illustrates higher temperatures in the light's vicinities. Thus, the predicted sensible heat flux slightly heats the air in the porous media zone.

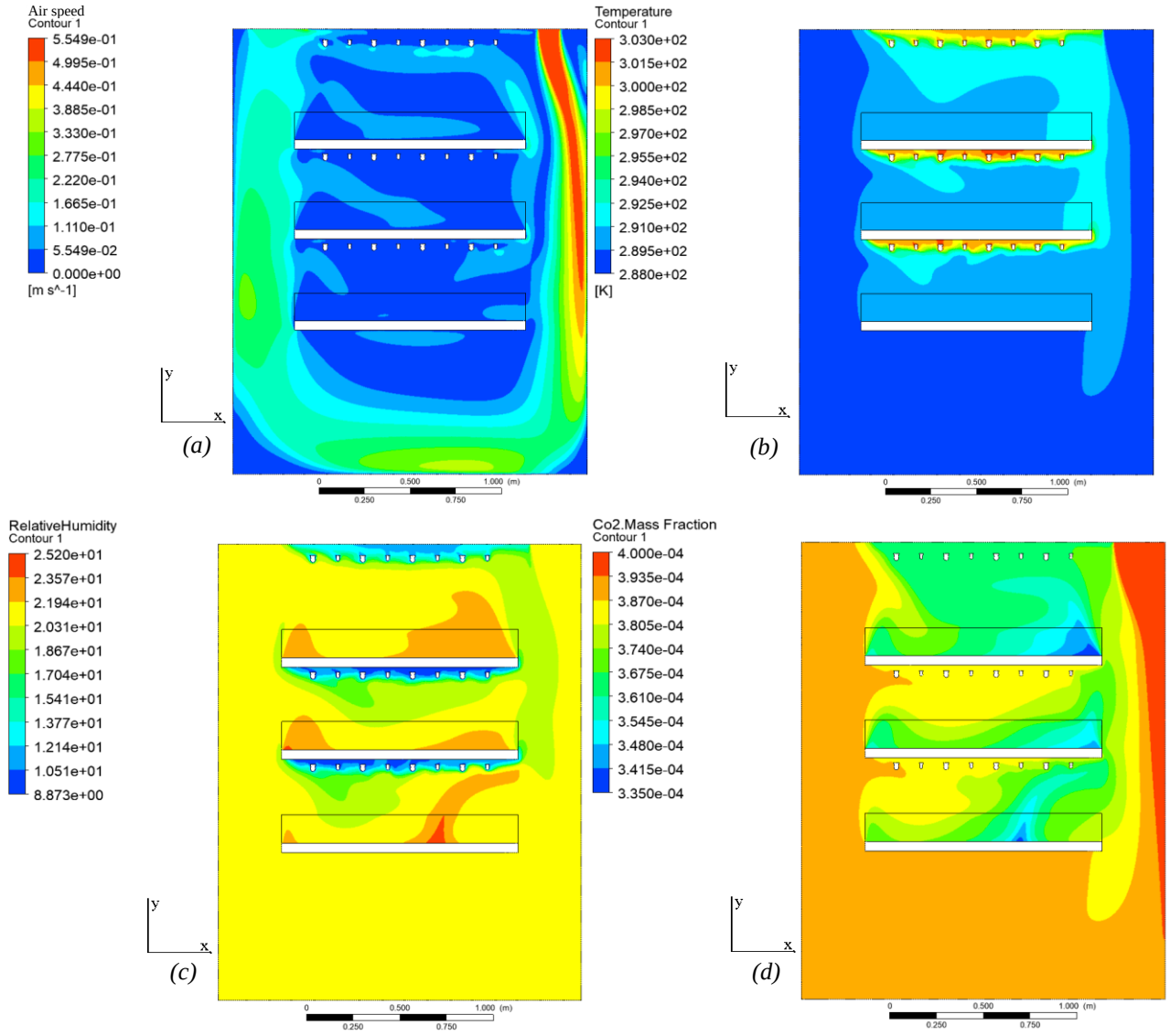

Figure 4 Contour plots of the modelled small-scale CEA-HD:
(a) air speed, (b) temperature, (c) relative humidity and (d) carbon dioxide concentration.

The relative humidity contour plot illustrated in Figure 4c clearly shows (1) heterogeneity of the values of relative humidity inside the three porous media cultivation zones and (2) a lower humidity near the lights, which is explained by the higher humidity capacity at higher air temperature. Finally, in terms of carbon dioxide concentration (Figure 4d), it can be noted that there is (1) still heterogeneity at the three cultivation zones and (2) there is a predicted concentration diminution of a few ppm at the outlet. This is consistent with the expected behaviour of the photosynthesis rate model presented in equation (16).

Parametric Analysis

A parametric analysis of the proposed model was performed to evaluate practical operational parameters to assess the direction and air speed of the supply air that minimize the variations of the field variables inside the modelled small-scale CEA-HD space. One metric used to assess the uniformity of a given field variable, as suggested by Zhang et al. (2016), is the coefficient of variation (CV) presented in equation (17) where the standard deviation (σ) is normalized by the mean (μ).

$$CV = \frac{\sigma}{\mu} \tag{17}$$

Three parameters are used to complete the parametric analysis: the inlet air speed, the x component of the inlet flow and the y component of the inlet flow. The inlet air speed is varied from 0.1 m/s to 0.5 m/s in 0.1 m/s increments while three inlet diffuser angles are parametrized: 0º (straight down), 22,5º and 45º towards the production multi-tiered racking. Table 2 presents the CFD simulations results with the inlet parameters used and the resulting coefficient of variation over the computed air speed. A minimum coefficient of variation of 44.2% is predicted in run 5 with the inlet conditions used for Figure 4.

Table 2. Results of the CFD parametric analysis over the computed air speed.

Run #	Inlet air speed (m/s)	X component	Y component	CV
1	0.1	0	-1	0.549
2	0.2	0	-1	0.679
3	0.3	0	-1	0.775
4	0.4	0	-1	0.517
5	0.5	0	-1	0.442
6	0.1	-0.5	-0.5	0.525
7	0.2	-0.5	-0.5	0.594
8	0.3	-0.5	-0.5	0.644
9	0.4	-0.5	-0.5	0.533
10	0.5	-0.5	-0.5	0.786
11	0.1	-0.38	-0.92	0.539
12	0.2	-0.38	-0.92	0.651
13	0.3	-0.38	-0.92	0.723
14	0.4	-0.38	-0.92	0.676
15	0.5	-0.38	-0.92	0.498

: values used for the results shown in Figure 4.

The CV values of Table 2 vary substantially from one configuration to another. Hence, the results indicate that the inlet parameters do have an effect on the airflow homogeneity. Also, The CV was only computed on the air speed field variable. Further investigation on determining target values for each field variable and a single weighted metric might prove useful for future research.

Discussion

The results presented in this paper seems to indicate that obtaining a uniform airflow distribution inside the experimental small-scale CEA-HD using the current air distribution system configuration might not be trivial. More advanced air distribution concepts or cultivation apparatus designed with airflow requirements might be necessary to achieve uniform environmental conditions inside the CEA-HD space such as distributed fans or hot and cold aisles with a raised floor. While a two-dimensional analysis of the flow inside the CEA-HD is informative, the nature of the flow is tridimensional. The results of a 3D model should be able to inform the design process even further. One drawback of calculating the energy balance of the crop model in each cell is the increased calculation time with mesh refinement of the porous media domain. A compromise between accuracy and computing time must be determined to keep simulation time acceptable. Indeed, even with a two-dimensional model, the iterative solution coupled with the species transport model yielded difficult convergence and long simulation time (hours). The short-wave radiation flux (PAR) absorbed by the crops is currently modelled as a constant for all the porous media domain. An irradiation extinction model (such as beer's law) could be added to further represent actual crop conditions and obtain an irradiation profile over the height of the crop. In the proposed CFD model, the influence of the growing rack on the airflow is neglected. The hypothesis is that it does not influence the main flow characteristics inside the CEA-HD. Further evaluation of the effect of the growing rack might provide insights on how to better deign these to promote airflow to the crops.

The results obtained in this study have only been validated for a small-scale CEA-HD space. The scale of the CEA-HD space used in the validation experiments might be too small to assess adequately stratification phenomena. In-situ characterization of the spatial distribution of indoor field variables might provide more insight at the commercial scale. More extensively valid recommendations on airflow parameters bounds and applicability range might be uncovered by applying the proposed methodology to a commercial scale CEA-HD.

Further investigation into the models used for the stomatal resistance, aerodynamic resistance and carbon dioxide generation should be performed to assess the variability of the CFD predicted spatial distribution of the field variables given different input models. This analysis could provide an idea of the variability of the high concentration areas given

different model assumptions prior to validation experiments. While a parametric analysis is useful, an optimal configuration is better. The inlet parameters could be integrated into Ansys Workbench and into optimization algorithms to minimize the coefficient of variation (CV) even if an optimal solution could prove computationally expensive in the present context. Hence, typical air distribution configurations should be identified prior to attempt computing optimal parameters. Other metrics such as the air distribution index (Karimipanah et al., 2008), the air residence time (Fontanini et al., 2016) might be useful to perform such an optimization task.

In future work, validation of the model predicted air speed field could be performed with a particle image velocimetry (PIV) measurement system. This could be informative to assess the precision of the current model as only integral quantities could be obtained. Also, the proposed model is applied to a small-scale CEA-HD space with a relatively simple air distribution system. Still, the same method could be used to evaluate the performance of more advanced air distribution and design novel CEA-HD space growing configurations. Instead of using a parametric analysis, coupling the developed CFD model with an optimization algorithm could have been used to try to find an optimal diffuser configuration for the currently existing linear slot diffuser in the small-scale CEA-HD. Integration of the local heat and mass exchanges should provide a theoretical estimate of simpler surface coefficients. These coefficients may prove useful to future HVAC system designers by providing a more accurate calculation of hygrothermal loads.

Conclusion

In this study, a CFD modelling approach that considered the impact of the crops on the distributed indoor environment is proposed. It included modelling the crop impingement on airflow as well as the transpiration and photosynthesis process. A parametric analysis was then performed to predict two practical operational parameters: the supply air speed and jet orientation minimizing the environmental conditions coefficient of variation in the crop domain, modelled as a porous media. As more commercial scale CEA-HD spaces emerge, engineers will be asked to answer practical operational questions about these types of growing spaces. This paper aims to provide them with a step forward in terms of CEA-HD space air distribution modelling so that innovative growing room designs can be evaluated with commercial CFD software with the evaporation and photosynthesis processes included.

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