Modelling plant transpiration and leaf climate using CFD

Wito Plas\textsuperscript{1,2} and Michel De Paepe\textsuperscript{1,2}

\textsuperscript{1}Department of Electomechanical, Systems and Metal Engineering, Ghent University, Sint-Pietersnieuwstraat 41, 9000 Ghent, Belgium
\textsuperscript{2}Flanders Make@UGent – Core lab EEDT-MP

Email: wito.plas@ugent.be

Abstract. Research into vertical farms or plant factories is steadily increasing over the years, as the demand for sustainable food production and a shift to more environmental friendly food production is occurring. Modelling plant climate in these confined spaces is therefore essential to guarantee optimal growing conditions. Modelling of plant climate has already been done in greenhouses, but at length scales much bigger than individual leaves. In this study, one single plant will be modelled, using computational fluid dynamics and by incorporating additional source terms in the relevant transport equations. Plants are modelled using the big leaf approach, where a plant is modelled as one artificial leaf. Water vapour flux in plants is controlled by two resistances in series, the aerodynamic resistance, which is a function of the boundary layer around the leaves and the stomatal resistance, which is the resistance against water vapour transport in leaves. Two different plants are studied, impatiens pot plant and basil plants. Values of stomatal resistance for these crops are obtained from literature or were measured. Evapotranspiration was compared with the Penman-Monteith equation.

1. Introduction
Vertical farms or plant factories are becoming more and more widespread, as the demand for sustainable food production and a shift to a more environmental friendly food production is increasing [1]. Climate control in these confined spaces is more stringent, as these crops are grown in confined spaces with less open air, contrary to crops being grown in greenhouses or out in the field. Optimal growing conditions are essential to ensure the best quality of produce.

Modelling leaf transpiration is therefore essential to assure the plant can have its optimal plant climate. The plant will actively influence its local climate through the use of stomata, microscopic little pores on the surface of the leaf through which water vapour passes and CO\textsubscript{2} is absorbed. Predicting transpiration of a plant or a canopy was first modelled, using the Penman-Monteith equation, where a plant is considered to be a \textquoteleft big leaf\textquoteright [2]. This is a purely analytical equation, predicting evapotranspiration in function of the incoming radiation and the vapour pressure deficit in the air and inside the plant. As computational power increased, computational fluid dynamics started to be used for predicting the climate in greenhouses. These simulations also considered the plants to be a big leaf and defined a plant zone inside of the greenhouse. This plant zone has a considerable size and includes several plants. Plants that have been studied, are for example tomato [3] and impatiens pot plant [4]. All of these studies have looked at collections of plants. No study has been done where one single plant has been looked at.
2. Method

The studied crop in this paper is basil. Evapotranspiration and leaf area density are measured for this crop in a growth experiment, performed in a vertical farm in September 2019. This data is used to make a CFD-transpiration model in Fluent. The plant is modelled as a stacked cylinder with a fixed radius and a certain height, which were measured during the experiment. In addition to basil, impatiens pot plant with the same geometry is studied to see the effect of stomatal resistance on radiation.

A uniform velocity profile was applied at the inlet zone, a pressure outlet at the outlet zone. The bottom wall was a non-slip wall. The surrounding walls were no shear walls. The calculation domain and the boundary conditions are given in Figure 1. The plant is meshed using a tetrahedral mesh with a body-sizing of 2mm, the surrounding air as 5mm, giving it a total mesh size of 5,072,398 cells. Further refinement has been applied at the walls.

The CFD code in Fluent is altered to incorporate the effects the plant has on its environment. The plant is considered to be a generalized leaf, or a ‘big leaf’. The plant influences its environment in three ways; momentum loss of the flow, source of water vapour and sink of energy. All three are modeled by incorporating an extra source term in the relevant transport equation. The plant will exert a certain drag force on the incoming air, but it will also allow air flow to pass through it. The plant zone therefore is modelled as a different zone than the air zone, but with a momentum source sink. The momentum source sink is first defined by Thom [5] to be in the form of Equation 1 and is a modified version of the Darcy-Forchheimer law for flow through porous medium. $C_d$ is the drag coefficient of the crop, $\rho$ the density of air, $u$ the velocity and $LAD$, the leaf area density of the plant. This is the ratio of leaf area to total plant volume. This value is measured for basil at different growing stages. The value used in this study is 12.43. The value for drag coefficient is 0.32, which is the same value used for tomato and impatiens plant [3,4].

$$S_d = -LAD \cdot C_d \cdot \rho u^2$$  

Leaf transpiration is modelled by including an extra source term for the production of water vapour. This source term is equal to the amount of transpiration by the plant divided by the plant volume. The total amount of water vapour produced is found by applying the conservation of mass over a leaf. Water vapour will diffuse out of the leaf at a certain rate through the stomata and this diffusion rate is determined by the stomatal resistance, $r_s$. From the surface of the leaf, the water vapour encounters an extra resistance in the boundary layer around the leaf, the aerodynamic resistance, $r_a$. The leaf is said to be at an absolute humidity level, equal to that of the leaf temperature. Combining these equations gives Equation 2 for the water vapour production. $\omega^*(T_l)$ is the saturated absolute humidity at leaf temperature and $\omega_a$ is the absolute humidity in the surrounding air.

$$S_{w,t} = \frac{\rho}{r_s+r_a} \cdot \frac{\Delta_{leaf}}{V_{leaf}} \cdot (\omega^*(T_l) - \omega_a) = \frac{\rho}{r_s+r_a} \cdot LAD \cdot (\omega^*(T_l) - \omega_a)$$  

To include the effects of radiation and evaporation of the water inside the plant canopy, an energy source term is added. This source term is found by applying the conservation of energy over the plant, Equation 3.
\[ R = Q_{\text{sen}} + Q_{\text{lat}} = 2hA_{\text{leaf}}(T_i - T_{\text{air}}) + \frac{L_\varepsilon \rho_{\text{L}}}{r_a + r_s} A_{\text{leaf}}(\omega^* (T_i) - \omega_a) \]  

(3)

where \( Q_{\text{sen}} \), the sensible part of the heat is that being absorbed by the plant, \( Q_{\text{lat}} \) the latent heat of the water that is being evaporated and \( R \), the incoming radiation. The total generated heat of the plant can be expressed as the sensible heat divided by the volume of the canopy, Equation 4.

\[ S_R = \frac{Q_{\text{sen}}}{\nu \text{vol}} = R \cdot \frac{A_{\text{leaf}}}{v_{\text{leaf}}} - \frac{L_\varepsilon \rho_{\text{L}}}{r_a + r_s} \frac{A_{\text{leaf}}}{v_{\text{leaf}}} (\omega^* (T_i) - \omega_a) = L\text{AD} \left( R - \frac{L_\varepsilon \rho_{\text{L}}}{r_a + r_s} (\omega^* (T_i) - \omega_a) \right) \]  

(4)

Radiation is modelled using Beer’s law of extinction through a canopy, Equation 5. \( k_c \) is the extinction coefficient of the crop and is set to 0.78. \( R_n \) is the net long wave radiation on top of the canopy, produced by the LED-lights and is equal to 128W/m².

\[ R = R_n \cdot \exp(-k_c L\text{AD}(H - z)) \]  

(5)

The aerodynamic resistance is inversely proportional to the convection coefficient. The convection coefficient is determined by using a correlation for laminar flow over a flat plate, Equation 6, as Reynolds numbers are in the order of 400. The aerodynamic resistance is linked to the mass transfer coefficient, which in turn is linked to the heat transfer coefficient by the Lewis number. Inserting all the variables and rearranging for \( r_a \), gives Equation 7, which is inversely proportional to the root of the velocity, \( v \). \( C_p \) is the specific heat of air, \( k \), the thermal conductivity, \( L \) the specific length of the leaf and \( v \), the kinematic viscosity of air. If velocity increases, aerodynamic resistance decreases and the plant will evaporate more water. Velocity in turn is affected by the momentum source term.

\[ Nu = \frac{hL}{k} = 0.664 \cdot \frac{Re_{1/3} Pr a^{1/3}}{C_\theta} \]  

(6)

\[ r_a = \frac{\rho C_p}{h} L e^{2/3} = \left( \frac{C_p}{h} \right)^{0.5} \frac{0.664}{k} Le^{2/3} \left( \frac{L}{v} \right)^{0.5} \]  

(7)

Stomatal resistance is a measure of how well the plant can diffuse water vapour and CO₂ through its stomata. Stomatal resistance is a function of incident radiation, vapour pressure deficit and CO₂ concentration. The effects of radiation and vapour pressure deficit will only be accounted as these are the most dominant factors. Stomatal resistance in function of radiation, \( R_n \) and vapour pressure deficit, \( D \) (in kPa) is found in literature for impatiens pot plant, Equation 8. The value for stomatal resistance for basil is fixed at 330s/m, a value derived from measured data.

\[ r_s,\text{impatiens} = 150 \cdot \frac{169 + R_n}{184 R_n} (1 + 0.005(D - 1.2)^2) \]  

(8)

Validation of the CFD-model is performed by using the Penman-Monteith (PM) equation. This is an analytical expression, developed by Penman and adopted by Monteith. Climatic parameters needed in the equation are taken from the conditions inside the plant zone.

\[ AE = \frac{s R_n + \rho_{\text{L}} A l C_p a_a (\omega^* (T_i) - \omega_a)}{s + y (1 + r_a)} \]  

(9)

3. Results and discussion

Two different plants are modelled, impatiens pot plants and basilicum. The velocity distribution for the two plants is the same, as the same parameters are used in the momentum sink terms. Velocity distribution is shown in Figure 2. Due to the drag in the canopy, velocity is stopped from 3.4m/s at inlet to 1.87m/s after the plant. The value of 1.87m/s is used to calculate the aerodynamic resistance in Equation 6 and 7.

In Figure 3, the production of water vapour in the plant is plotted for impatiens plant and basil. The production of water vapour shows a vertical profile in the impatiens plant case, with the most water vapour being produced at the top layers of the plant. This can be explained by the fact that at the top of the plant, incoming radiation is the highest and that the plant will cool itself down in order not to overheat. Radiation in the plant itself drops exponentially, stomatal resistance increases and less water vapour is produced. Aerodynamic resistance (±80s/m) is low, due to the high velocity throughout the plant (1.87m/s). There is therefore no horizontal gradient in the water vapour production for impatiens.
plant. Stomatal resistance is uniform for the basil plant and water vapour production is hence uniformly modelled throughout the plant.

In Table 1, the total simulated transpiration, the experimental transpiration obtained for the basilicum plant and the transpiration calculated via the Penman-Monteith equation are listed. The simulated value of transpiration for basil differs with 26% from the measured value. The difference can be attributed to the error made by estimating a constant stomatal resistance over the plant. Measuring the stomatal resistance of basil could lower this error. The transpiration predicted by the PM-equation underpredicts the CFD-transpiration and the measured value for both impatiens and basil by a large factor. This can be explained by the fact that this equation was used to estimate transpiration of plants under natural light conditions, where transpiration is mostly controlled by the incoming radiation. LED lights however have lower energy outputs as they only emit light in the photosynthetic active range. The factor $R_\text{n}$ in Equation 9 is therefore lower.

|        | ET values from CFD, Penman-Monteith equation and measured value. |
|--------|------------------------------------------------------------------|
|        | $\times 10^{-7}$kg/s water | CFD | PM-equation | Measured |
| Impatients | 2.38                 | 0.85 | /           |
| Basil    | 5.49                 | 0.81 | 4.05        |

4. Conclusion
An individual basil and impatiens plant have been simulated in CFD, by incorporating source terms in the transport equations. It was possible to calculate transpiration inside the plant and simulated values differ with 26% from measured data. Transpiration obtained from CFD is over predicting the transpiration obtained by the Penman-Monteith equation and this can be explained by the fact that this equation was formulated for transpiration in plants under natural light conditions, not for plants grown under LED-lights.

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