

# SIMULATING HEAT AND MASS TRANSFER OF A PLANT USING AN EXPLICIT PLANT GEOMETRY

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## 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 those studies, plant geometry is modelled implicitly in CFD using source terms that add an extra momentum loss term, a transpiration flux and an energy sink at the plant zone. These simulations can be sufficient for large spaces, like greenhouses, but can be too inaccurate for the ventilation systems used in vertical farming systems. In this study, plant architecture with actual leaves is modelled explicitly. This method allows for the accurate prediction of boundary layer formation around the leaves and can be a more accurate tool for simulating air flow and humidity patterns inside a crop. Plant structure, leaf area and transpiration are determined experimentally and are used as input parameters. The explicit geometry is compared to implicit simulations. Simulations are validated, using measured values of relative humidity and temperature around a basil plant. Simulated absolute humidities in the implicit and the explicit plant model correspond well, whereas temperature only agrees well in the implicit plant model.

## INTRODUCTION

Research in vertical farms or plant factories is steadily rising over the years. A vertical farm or plant factory is a closed environment in which radiation, ventilation and all other external plant parameters are controlled. Since this is a closed environment, the need for a decent ventilation system in such a plant factory arises. This ventilation system needs to make sure that plants are still able to fully transpire and grow in their optimal conditions. In order to obtain the optimal climate conditions and best flow patterns of air in such a plant factory, Computational Fluid Dynamics, CFD can be used to investigate flow fields around the

## NOMENCLATURE

|           |                                   |                                     |
|-----------|-----------------------------------|-------------------------------------|
| $A$       | [m <sup>2</sup> ]                 | Area                                |
| $C_d$     | [-]                               | Drag Coefficient                    |
| $C_p$     | [J/kgK]                           | Specific heat capacity              |
| $d_v$     | [m]                               | Characteristic Length               |
| $ET$      | [mg/s]                            | Plant Transpiration                 |
| $H$       | [m]                               | Plant Height                        |
| $k_c$     | [-]                               | Extinction Coefficient              |
| $LAD$     | [m <sup>2</sup> /m <sup>3</sup> ] | Leaf Area Density                   |
| $L_v$     | [J/kg]                            | Latent heat of evaporation          |
| $\dot{m}$ | [kg/s]                            | Mass Flow Rate                      |
| $R$       | [W/m <sup>2</sup> ]               | Radiation heat                      |
| $r$       | [s/m]                             | Resistance to water vapour transfer |
| $T$       | [K]                               | Temperature                         |
| $v$       | [m/s]                             | velocity                            |
| $Vol$     | [m <sup>3</sup> ]                 | Volume                              |
| $q$       | [W/m <sup>2</sup> ]               | Heat flux                           |
| $z$       | [m]                               | Cartesian axis direction            |

### Special characters

|               |                       |  |
|---------------|-----------------------|--|
| $\lambda$     | [W/mK]                | Thermal Conductivity                                 |
| $\rho$        | [kg/m <sup>3</sup> ]  | Density  |
| $\nu$         | [m <sup>2</sup> /s]   | Kinematic viscosity                                  |
| $\omega$      | [kg water/kg dry air] | Absolute humidity ratio                              |
| $\omega^*(T)$ | [kg water/kg dry air] | Saturated absolute humidity ratio at temperature $T$ |

### Subscripts

|        |              |
|--------|--------------|
| $a$    | aerodynamic  |
| $amb$  | ambient      |
| $H_2O$ | water vapour |
| $in$   | incoming     |
| $leaf$ | leaf level   |

plant and inside the factory. When CFD is used to study the microclimate inside a plant factory, the uniformity of air flow in a certain zone can be investigated in order to make sure plants receive a uniform airflow [1]. This method only solves the flow equation and ignores the transpiration and energetic fluxes that occur inside a plant factory, and CFD-studies where transpiration is included are therefore vital. A more recent study also studies air flow uniformity inside a plant factory and incorporates LED heat radiation for a lettuce plant[2]. The author uses a porous medium approach to model the drag effect on the flow. Transpiration and energy exchange with the environment are omitted however.

Most CFD studies which involve plant behaviour are focused on

solving the Navier-Stokes equations in a greenhouse type environment, where overall dimensions are much bigger. Plants in such a model are modelled implicitly by adding relevant source terms to the momentum, energy and water vapour equation. This can be combined with meteorological data which then can be used to validate the CFD-model [3; 4; 5]. In such a model, plant behaviour is then defined using measured average properties inside the canopy. These greenhouse studies lack the physical complexity of a plant, and model the plant as a black box, where transpiration and energy exchanges happen. The simulation results are in turn validated with experimental data. Another author studies mass and energy transfer at the leaf level of one leaf for low light levels [6]. Münger cells, small cells in which temperature and humidity are measured at the inlet and outlet of the domain, are used for experimental verification of the numerical code. Numerical and experimental results agreed well for relative humidity values, but diverged more for temperature values. Furthermore, only one single leaf could be investigated.

There are authors who include the physiological structure of plants (trees), but omit the transpirational behaviour of plants. In these studies, trees with explicitly drawn branches are put in a wind tunnel and are simulated in CFD as well [7]. Results are validated using measured velocities in the wake of the tree. Such simulations can offer good insight in flow patterns for airflow in open urban environments, but its data can be difficult to extrapolate for plant factory applications.

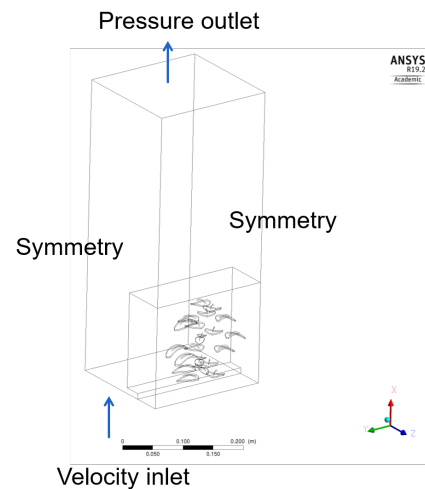
In previous studies either plant transpiration and energetic fluxes are omitted when modelling plants or the plant structure itself is omitted. This conference paper aims to study both the air flow around the plant, as well as to include the transpiration flux of a living plant.

## NUMERICAL METHOD

The aim of this study is to investigate whether an implicit plant model, where transpiration, energy exchange and momentum loss is modeled by adding additional source terms is a valid alternative for an explicit plant model, an actual plant, where transpiration and energy exchange happen at the leaf level. In order to investigate this, two different simulation domains are constructed. An explicit plant domain, with a physical plant with actual leaves and a second domain where plants are implicitly modeled using a cylindrical porous zone. Results are validated against previously obtained experimental results. The plant was modeled after a basil plant, as this plant has a relatively easy to describe geometry, and experimental growing data of the plant structure, transpiration values as well as experimental temperature and humidity distributions are present. The explicit plant model was constructed using Ansys Design Modeler. The plant was cut up along one symmetry line to limit the calculation costs. The plant model consists of a total of 23 number of leaves ordered centrally along a vertical axis, see Figure 1. The amount of leaves is chosen so that the total leaf area resembles the measured leaf area of an actual basil plant in that stage of life, namely 347.92cm<sup>2</sup>. The actual amount of basil leaves lie in the order of 155 to 200. There are however a lot of small leaves present in a

basil plant, and including all of them would make the simulation even more mesh heavy. Out of mesh considerations, the stems of the plant are omitted as well. If stems are included in the geometry, the danger of skewed mesh cells in the zone around the leaf and the stem could occur. Furthermore, the only use of stems inside a plant model would be the extra slowing down of the flow. This factor is thus under predicted, and pressure drop only occurs due to the presence of the leaves. In the implicit model, the plant is modeled using a cylindrical shape, with a diameter of 15cm. This corresponds with the outermost inscribing cylinder around the geometrically drawn plant. Plants inside the plant factory are ventilated at the bottom. Therefore, there is a velocity inlet at the bottom of the domain and a pressure outlet at the top. All side walls are modelled as symmetry planes. In Figure 1 the simulation domain of the explicit model is shown. In Figure 2, the domain size of the implicit model is shown. Both cases have equal simulation domain sizes.

The Reynolds numbers in the implicit model is 275 and a laminar solution is therefore opted for. In the explicit case, a turbulence model is used, as there will be unsteady flow over blunt objects, creating vortices downstream of the leaves. The  $k-\omega-SST$  turbulence model is therefore used to solve for turbulence. The used air mass flow rate for one plant in the experiment is 0.00030028 kg/s, which corresponds with a velocity at the inlet of 0.025m/s. The sizing of the domain in the implicit model does not need to be too high, since no boundary layer needs to be resolved. Instead, the interaction of the different source terms is investigated. The total number of elements in the implicit model is equal to 105,069 elements. The boundary layer around the leaves however needs to be adequately captured, and mesh size is chosen so that  $y^+$ -values around the leaves are all below 1. The Number of elements in the explicit model is 24,530,464 and a solution for the explicit model is therefore more computational heavy than the implicit model.



**Figure 1.** Simulation domain

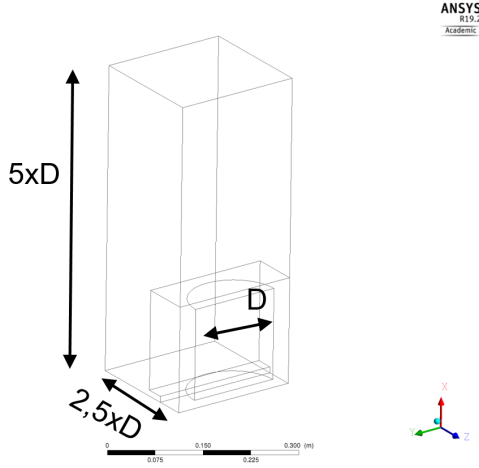


Figure 2. Implicit model: domain size

### Governing equations for the plant model

In order to investigate the differences between an explicit and an implicit model, a day-time plant model is investigated for both cases. The implicit model and explicit plant model both need extra equations to take into account the plant is transpiring and interacting with its environment. In the implicit model, plant transpiration rates will be fixed and will not be a function of external parameters, such as incoming radiation, Vapour Pressure Deficit, VPD or flow rates. An experimental data-set will be used to validate both simulations.

The explicit plant model is described by defining a heat flux at the leaf side and by defining a specified mass fraction of humid air at the bottom side of the leaf's surface. Most leaves only transpire on the underside of the leaf's surface, as the cells that cause transpiration, stomata, are located on the underside of the leaf. The heat flux at the underside of the leaf is given by the following equation, where  $R_{in}$ , the radiation heat from LEDs, sunlight or other sources is.  $ET$ , is the transpiration rate of the plant, expressed in mg water per second and  $A_{leaf}$  is the total leaf area. This is the same transpiration rate that is used in the implicit model and equals the experimental measured transpiration rate.

$$q_{leaf} = R_{in} - L_v \cdot \frac{ET}{A_{leaf}} \quad (1)$$

The radiation hitting the leaves,  $R_{in}$  is described in this simulation in a similar manner as is done in an implicit model, by using the Beer-Lambert extinction correlation for radiation extinction inside a canopy, Equation 2.  $k_c$  is the extinction coefficient inside the canopy, a value of 0.95 is typically found in literature for well watered ornamental plants [4] and is also used in this study.  $LAD$  is the leaf area density of the plant, this is the ratio of the total leaf area to the plant volume.  $R_{top}$  is the incoming radiation on top of the canopy and  $H$ , is the height of the plant

$$R_{in} = R_{top} \cdot \exp(-k_c \cdot LAD(H - z)) \quad (2)$$

It is not possible to directly input the amount of transpiration in the explicit case. Instead of this approach, the absolute humidity at leaf level is defined using the conservation of mass between the inside of a leaf and the ambient air. This is the same approach, used by Roy et al [6]. Using this method a fictitious absolute humidity at leaf level can be defined, see Equation 3.

$$\omega_{leaf} = \frac{r_a \cdot \omega^*(T_{leaf}) + r_s \cdot \omega_{amb}}{r_s + r_a} \quad (3)$$

In this equation,  $r_s$  is the stomatal resistance of the leaf, which can be measured using a porometer.  $\omega_a$  is the absolute humidity in the air surrounding the leaf. The absolute humidity in the air surrounding the leaf will vary considerably, and it is therefore opted to use the absolute humidity of the incoming air as a proxy for the absolute humidity of the air surrounding the leaf.  $\omega^*(T_{leaf})$  is the saturated absolute humidity at the leaf temperature. In order to decouple the solution for the energy and the water vapour equation, it is chosen to use a constant value for  $T_{leaf}$ , namely the measured experimental value of 299.65K.  $r_a$  in this equation is the aerodynamic resistance, which is a function of the boundary layer around the leaf, which in turn is a function of the leaf size, shape and velocity over the leaf. Experimental correlations exist for this aerodynamic resistance and those are mostly derived from flat plate theorem. A correlation used by Majdoubi et al. for this resistance is given in Equation 4 [5].  $\rho$  is the density of air,  $C_p$ , is the specific heat capacity of air,  $\lambda$ , is the thermal conductivity of air.  $d_v$  is the characteristic length of the leaf, the width of the leaf.  $\nu$ , is the kinematic viscosity of air and  $v$ , the mean velocity of air inside the canopy. Using the value of the velocity at the inlet and filling it in this correlation, gives an aerodynamic resistance of 900s/m. This is a high value and thus corresponds with bad overall mass transfer. In the first simulation, a value for the aerodynamic resistance of 200s/m, a better ventilated case, is used in order to see the difference between the two cases. The second case corresponds with an infinitely high aerodynamic resistance, which then indicates that  $\omega_{leaf} = \omega^*(T_{leaf})$ .

$$r_a = \frac{\rho C_p}{0.288\lambda} \cdot \left(\frac{d_v \cdot \nu}{v}\right)^{0.5} \quad (4)$$

Using this method, the absolute humidity at the leaf's surface is the weighted average of the humidity of the in blowing air and the maximal humidity at leaf surface. Two different values for absolute humidity at leaf surface will be investigated, one where  $r_s$  and  $r_a$  are chosen and one where the absolute humidity at leaf level is at its maximum value, more precisely,  $\omega^*(T_{leaf})$ . The transpiration rate of the plant can be calculated by multiplying the mass flow rate with the absolute humidity at the outlet of the domain and the inlet of the domain. This in turn can then be compared to the values used in the implicit model.

The implicit model is defined by adding extra source terms in the water vapour, energy and momentum equation. These gov-

erning equations are listed in the underlying table. The change in momentum due to the presence of the plant, is done by modelling the plant as a porous zone, where momentum drag is added by using an inertial loss term.  $Vol$ , is the plant volume, which is measured experimentally and matches with the volume of the explicit model,  $C_d$  is the momentum loss coefficient of the crop. This value is 0.32 in this study, as multiple other studies also use this value to implement pressure drag over the plant [3; 4]

**Table 1:** Source terms for the implicit model

| Source Terms | Equation   |
|--------------|--|
| Momentum     | $S_m = -\rho C_d \cdot LAD \cdot v^2$                                    |
| Water vapour | $S_{H_2O} = \frac{ET}{Vol}$  |
| Energy       | $S_{Energy} = -L_v \cdot ET + k_c LADR_{in} \cdot \exp(-k_c LAD(H - z))$ |

In Table 2, values used in the simulations for the implicit and the explicit model are listed.

**Table 2:** Boundary conditions, used during the simulations

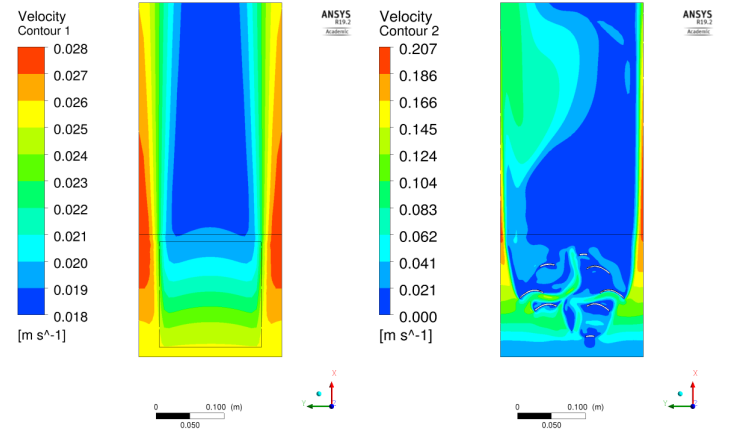
| Variable                                 | value | Variable  | value  |
|--|-------|---|--------|
| $R_{tot}$ (in W/m <sup>2</sup> )         | 71,1  | $\omega_{in}$ (in kg H <sub>2</sub> O /kg air)        | 0,0172 |
| ET (in mg/s)                             | 0.93  | $T_{in}$ (in K)                                       | 303.15 |
| LAD (in m <sup>2</sup> /m <sup>3</sup> ) | 21,96 | $k_c$   | 0.95   |
| $r_a$ (in s/m)                           | 200   | $A_{leaf}$ (in cm <sup>2</sup> )                      | 347,92 |
| $r_s$ (in s/m)                           | 300   | H (in m)  | 0.16   |
| $v_{in}$ (in m/s)                        | 0.025 | $\omega^*(T_{leaf})$ (in kg H <sub>2</sub> O /kg air) | 0.0215 |
|  |       | $\omega_{leaf_1}$ (in kg H <sub>2</sub> O /kg air)    | 0.019  |

## RESULTS AND DISCUSSION

### Velocity field

The biggest difference between both simulations is the presence of actual physical leaves in the explicit model. In the implicit model, the presence of the plant is modelled by adding an additional source term in the momentum equation. The presence of the actual leaves poses an obstacle for the flow of air through the plant. In Figure 3, the velocity field at the symmetry plane for the implicit and the explicit model is shown. Note that for most of the used figures, different color axis sizes are used, as this gives the biggest contrasts for each simulation. If the same color axis size is used for the velocity figure for example, one figure would exist out of one color, as the maximal velocity value of the explicit model ten times higher is than in the implicit model. The simulation solution in the implicit model is symmetrical and has lower overall velocities. Flow velocities above the plant are close to zero, as momentum decreases over the length of the plant. Temperature and humidity levels above the plant are thus expected to be uniform as well. The amount of flow retardation, is however mainly a function of the inputted drag coefficient and leaf area density. These values will as well influence what the maximal humidity in the plant will be and at what space in the plant this will happen. A thorough sensitivity study could therefore shed more light on this dependence. Overall velocities are also higher in the explicit model, as air passing through the plant has to pass through a more narrow channel. In both cases, velocity is the highest at the edges of the

domain, as it is easier for the air to pass along the edges of the plant than to traverse it. This effect can cause a lower transpiration value for the explicit case, as there is more air that bypasses the plant than traverses it. A solution could be for future simulations to limit the domain size even further and force the flow to go through the plant.



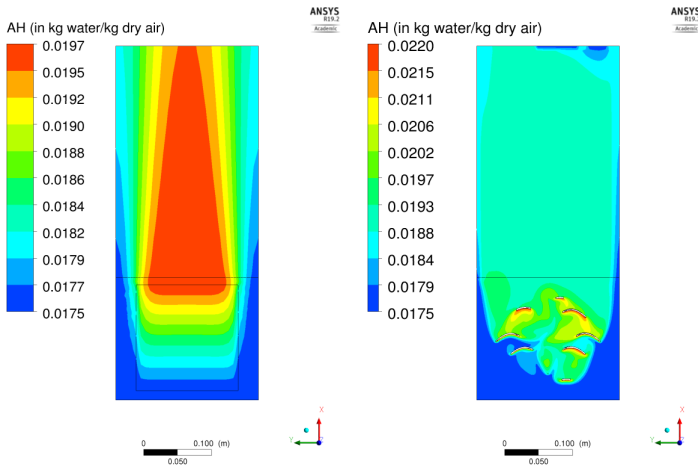
**Figure 3.** Velocity field in the implicit model (left) and in the explicit model (right)

### Water vapour

Water vapour is modelled by either defining a fixed absolute humidity at the leaf's surface or by adding an additional source term. The applied water vapour mass fraction at the leaf's surface is constant and is defined using a theoretical conservation of mass around the leaves. Two different absolute humidities at the leaf level are used. In the implicit model, transpiration is directly modelled by implementing transpiration using a source term in the water vapour equation. Water vapour fraction inside the plant, and the air above the plant for the implicit model and the explicit model with maximal absolute humidity at leaf level are shown in Figure 4. Humidity increases over the length of the plant in the implicit model, whereas high humidity levels are concentrated along the edges of the leaves. Due to the obstructions of the leaves, fresh air is not able to penetrate deeply into the core of the plant, and humidity is locally higher. Velocity above the plant is locally lower in the implicit model, and humidity is therefore stretched out in the space above the plants. The volume averaged value of humidity in the plant for the implicit model equals 0.0177 kg water/kg air, whereas this is 0.01825 kg water/kg air for the low humidity -leaf case, and 0.01926 kg water/kg air for the high humidity-leaf case.

Transpiration rate of the plant in the explicit model can be calculated by applying conservation of mass in the simulation domain, according to Equation 5. Applying this equation gives a transpiration of 0.24mg/s for an entire plant in the explicit model for the  $\omega_{leaf} = 0.019kg/kg$ -case.

$$ET = \dot{m} \cdot (\omega_{out} - \omega_{in}) \quad (5)$$

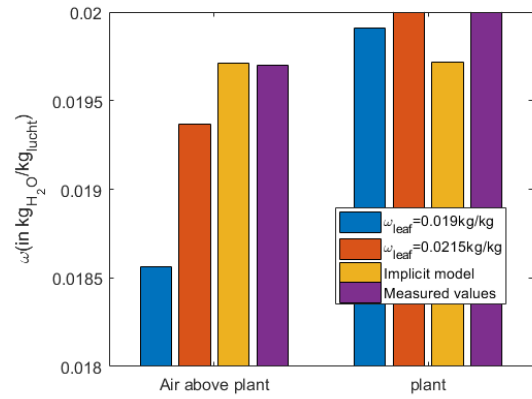


**Figure 4.** Absolute humidity field in the implicit model (left) and in the explicit model (right)

This value is more than 4 times lower than the measured transpiration. In order to obtain a higher transpiration, a second simulation is performed where the water vapour mass fraction at the leaf's surface is at its theoretic maximum, namely  $\omega^*(T_{leaf})$ , where  $T_{leaf}$ , the experimentally measured temperature is. Transpiration in this case equals 0.78mg/s, which is a value still lower than the measured transpiration. This underestimation of transpiration can possibly be attributed to the fact that a substantial amount of flow is not passing through the plant, but bypasses the plant along its sides in the simulation domain. In Figure 5, the maximal simulated absolute humidities in the air surrounding the plant and the air above the plant are plotted. The measured absolute humidity is also plotted in this graph. The low-humidity case does not agree well with measured values. The implicit case and high-humidity at leaf case correspond better with measured values. It is however still difficult to assess which model is better at predicting humidity patterns inside a plant. A more thorough experiment where humidity is measured along different points in the area above the plant could be done to check which model is the most adequate.

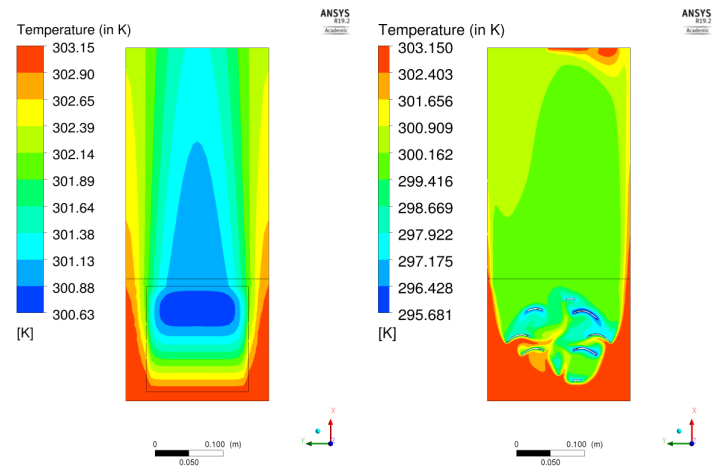
### Temperature

In the explicit model temperature is directly modeled by implementing a heat flux at the leaf side. This heat flux is governed by the measured transpiration and a theoretic incoming radiation, dictated by the Beer-Lambert equation for light extinction inside a canopy. In the implicit model, interaction with the plant is modelled by adding an additional source term in the energy equation. This equation consists of the latent cooling through evaporation of the plant and the heating through incoming radiation from the LEDs. In Figure 6, the temperature at the front symmetry-plane of both the implicit and the explicit model are shown. The minimum temperature simulated in the implicit model is 300.59K and in the explicit model is 295.68K. Measured temperature inside the plant is 299.65K. The implicit model is therefore better



**Figure 5.** Maximal simulated values of absolute humidity in plant and air above the plant

to accurately predict the temperature field inside the plant domain.



**Figure 6.** Temperature field in the symmetry plane for the implicit model (left) and in the explicit model (right)

Temperature inside the plant in the explicit plant model is possibly underestimated due to the assumption that transpiration is equally distributed among the leaves. It is possible that the uppermost leaves transpire more, due to the increased amount of radiation. When calculating the transpiration in the explicit model, it was also found that this value is lower than the experimentally obtained value for transpiration. A second simulation with this lowered transpiration could therefore have more realistic temperature distributions. The lowest value for temperature are also found in the uppermost leaves, where the incoming air is not able to penetrate the plant and influence the temperature of the leaf. This phenomenon is both similar for the implicit and the explicit-plant case.

Furthermore, a stagnant zone right above the plant in the implicit model can also be seen, and is similar as the stagnant zone in the

water vapour solution.

## CONCLUSION

Plant transpiration and energy exchange is investigated in this paper, by using an implicit model, a model where extra source terms are added to mimic plant behaviour and an explicit model, a plant model with realistically drawn leaves and where transpiration and energy exchange happen at leaf level. Velocity patterns in the implicit model are dependent on used input parameters, such as leaf area density and drag coefficient of the plant. A sensitivity study of momentum input parameters on maximal absolute humidity and temperature could therefore be performed for future calculations.

Absolute humidities in both the implicit and the explicit model with high humidity at the leaf's surface correspond well with measured absolute humidities. In both the implicit and the explicit model, a uniform zone of temperature and humidity is seen in the zone above the plant. A future experiment, where temperature and humidity is measured above the plant could be used for further validation of the models. Temperature in the implicit model also agrees well with measured values, whereas this diverges more in the explicit model.

An implicit method to determine humidity and temperature distribution inside a plant factory is overall a good, computational efficient choice to mimic plant behaviour, as the amount of transpiration of the plant is a priori known. This amount of transpiration still needs to be measured however, if the implicit model is used. Both the implicit and the explicit model are highly dependent however on calibration data (transpiration, incoming radiation, leaf area density, extinction coefficient,...). As the implicit model is only a function of this calibration data, this model is more dependent on this than the explicit model. At the moment, the added benefit of simulating air flow around realistically drawn leaves is not yet present, as simulated temperatures diverge too much with measured temperatures. Using different equations however, this approach can be promising to get an estimate of the total transpiration of a plant. The explicit model could be used to get a first idea of the amount of transpiration, which could be inputted in an implicit model, which then would

give an indication of the temperature field inside the plant. A simulation where an explicit plant is ventilated, using a more complex ventilation system, could also give more realistic values than the same case with an implicit model. Further research into the sensitivity of input parameters, and the relationship between air flow and temperature/humidity distributions is therefore essential and crucial.

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