CAESIM Validation Cases

Indoor Farming

CONTENTS

SECTION **PAGE**

1.0 CFD Model Verification / Validation

Three additional verification / validation cases have been completed. Two cases were selected for their relevance to the physics being simulated (i.e., related to plant transpiration and measured humidity values). A third verification case was generated/simulated to compare CAESIM results for air flow within an example plant factory. Additional simulations are required to model full 3D plant growth environments (see recommedation section).

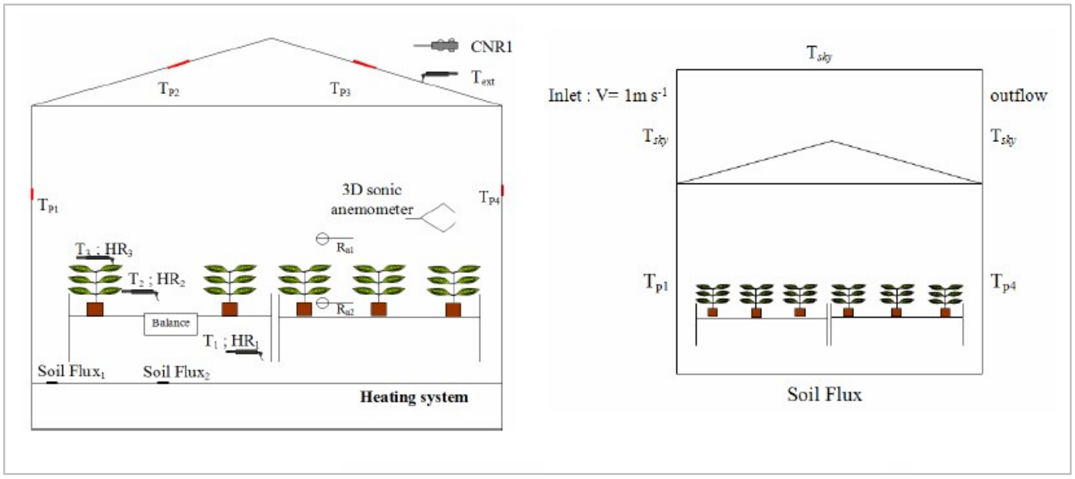
The following three sections provide a case description, CAESIM model defined, simulation results, and comparison to data presented in the publications.

1.0.a Distributed Climate Time-Evolution Inside a Glasshouse

Case Description

The publication "CFD Simulations of the Distributed Climate Time-Evolution inside a Glasshouse at Night", Morille et al, UP EPHor Environmental Physics and Horticulture Research Unit, Angers France, presents an experimental and numerical study. This publication provides details of an experimental setup to determine the time-evolution of greenhouse temperature and humidity distributions during night conditions.

> **Abstract**
>
> **Following the rise of energy costs and fuel scarcity, energy becomes today one of the main greenhouse crop production expenses. In this context, growers have to adapt their production system and climate management strategy in order to remain competitive, particularly at night when heat supply is often required and risk of condensation is enhanced. Numerical tools such as Computational Fluid Dynamics (CFD) can help predict the climate inside a greenhouse. CFD however is still scarcely applied in a dynamic way (Nebbali et al., 2011) and under night conditions (Montero et al., 2005). The aim of this study is to implement an unsteady 2D CFD model to predict the time-evolution of greenhouse temperature and humidity distributions all night long in winter, taking account of both radiative transfers and crop interactions with the inside climate. Beyond the classical conservation equations, a radiative submodel and a crop-submodel were activated. The latter takes account of both the heat and transpiration fluxes induced by the plants and their associated mechanical resistances which depend on the transfer mechanisms from the plant to the air. The boundary conditions were modified at each time step. Simulations were performed for a clear night on the basis of data collected in winter 2011 inside a 100 m^2 Venlo glasshouse with Impatiens New Guinea crop grown on shelves. Numerical results were validated against data recorded inside the greenhouse: roof temperature, inside air temperature, transpiration flux and air humidity. They highlight the influence of the dynamic boundary conditions on the evolution of the microclimate inside the greenhouse. This study demonstrates the ability of the CFD code to simulate the greenhouse climate evolution with realism. It also suggests a potential exploitation for designing the heating devices in order to optimize the inside climate and energy consumption for various outside conditions.**



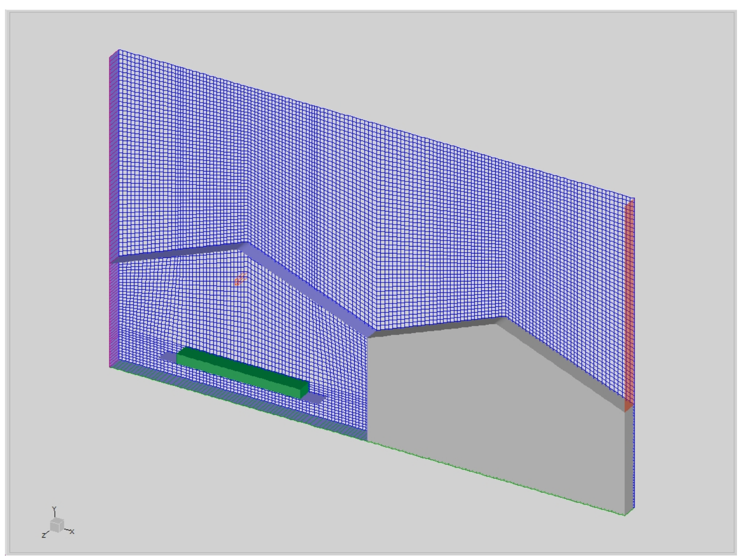
Schematic of Experimental Setup

Some assumptions were made in order to best match the physical conditions of the experiment. For example, zero radiation flux is assumed due to the nocturnal time of the experiment. Plant characteristics were set to the same as with Basil type plant (i.e., LAI = 4.0 and leaf length set to 4 cm).

CFD Model Definition

A 2D CFD model was developed to match the physical dimensions and phyics described in the publication. A porous media BC was defined for the plants. The customized plant transpiration module was activated to allow for plant heat generation and transpiration.

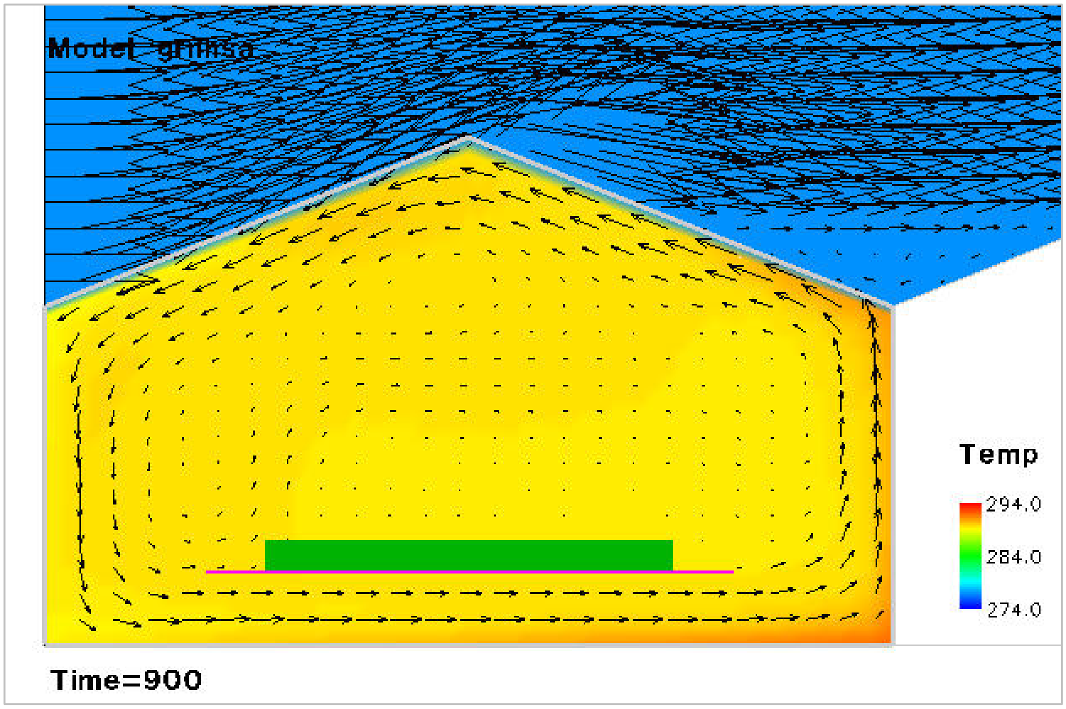
Turbulent flow
Heat transfer activated
Mesh distribution: 142 I 84 J 1 K
1 inlet BC
1 outlet BC
1 wall BCs
1 porous media BC
2 customized volumetric source BCs
1 gravity force BC
1 initialization field BC
Fluid I set to air (rho=1.177 kg/m^3)
Simulation timestep: 0.025 seconds
Tend: 900 seconds (model "grnhsa")
Tend: 3600 seconds (model "grnhsb")



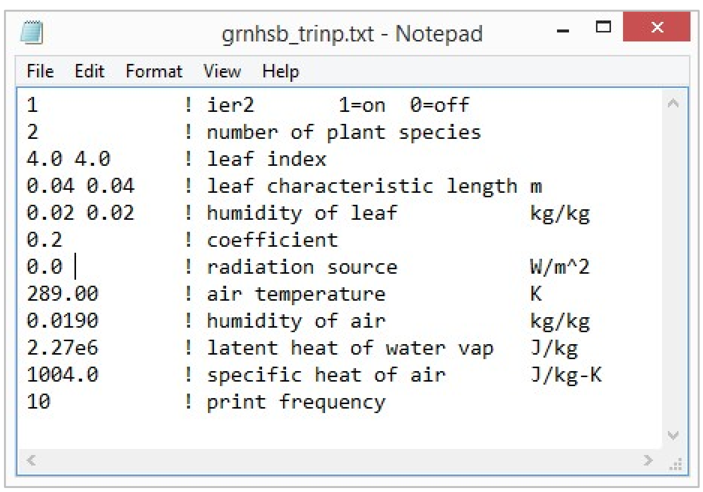
Note: CFD model "grnhsa" used to establish a steady-state flow field

Simulation Results

CFD Model "grnhsa" - Temperature Field



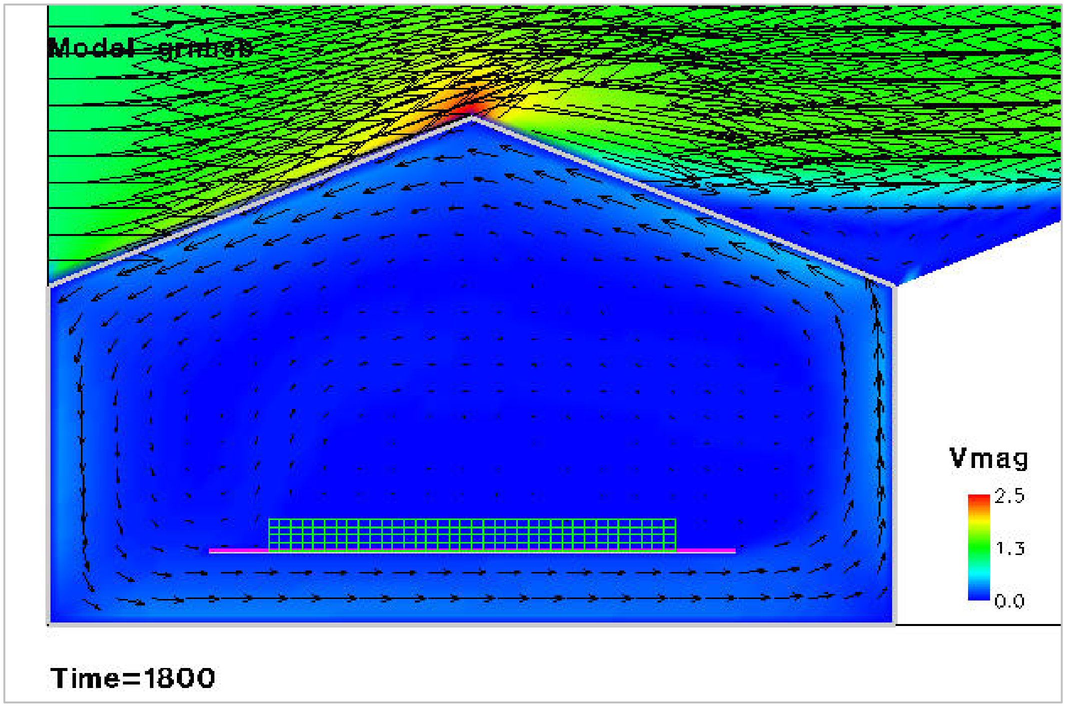
CFD Model "grnhsb" - Transpiration Module Input




```
1              ! ier2       1=on  0=off
2              ! number of plant species
4.0 4.0        ! leaf index
0.04 0.04      ! leaf characteristic length m
0.02 0.02      ! humidity of leaf           kg/kg
0.2            ! coefficient
0.0            ! radiation source           W/m^2
289.00         ! air temperature            K
0.0190         ! humidity of air            kg/kg
2.27e6         ! latent heat of water vap   J/kg
1004.0         ! specific heat of air       J/kg-K
10             ! print frequency
```

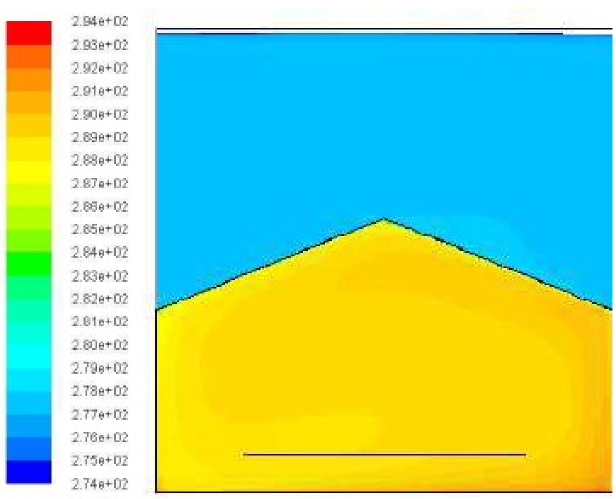
The steady-state flow and temperature fields resulting from the execution of CFD model "grnhsa" ~900 transient seconds, are used as a restart condition for CFD model "grnhsb" with the plant transpiration module activated. CFD model "grnhsb" is subsequently executed an additional 3600 seconds (1 transient hour).

CFD Model "grnhsb" - Velocity Magnitude

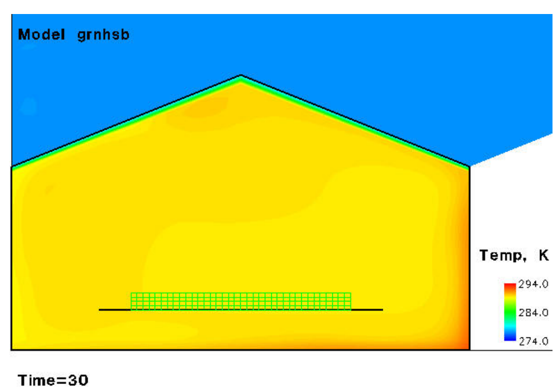


Numerical Comparison Analysis

Temperature Fields



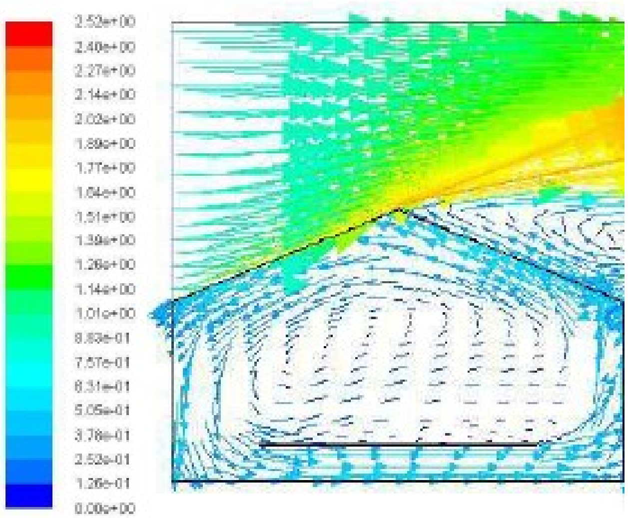
Publication

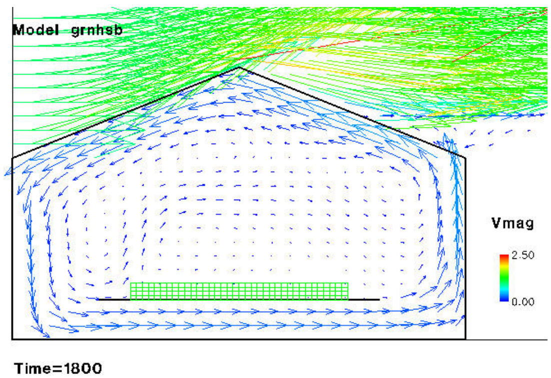


CAESIM

Very comparable temperature fields are observed between publication and CAESIM simulation results. There is a noticeable "build-up" of heat located at the bottom right corner of the greenhouse structure.

Velocity Fields

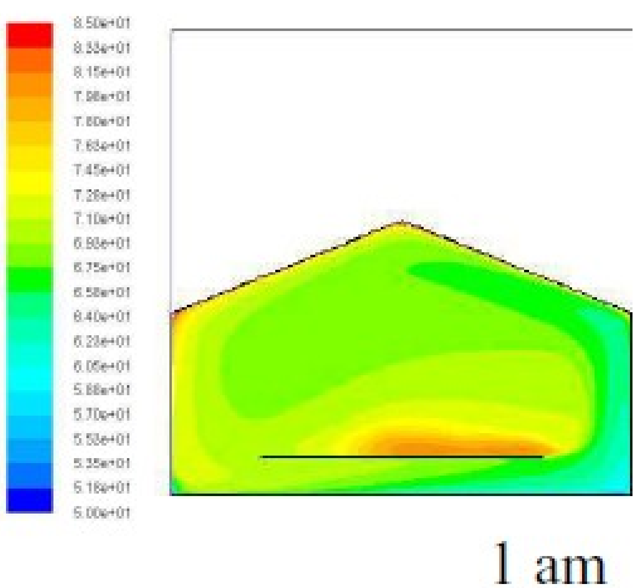


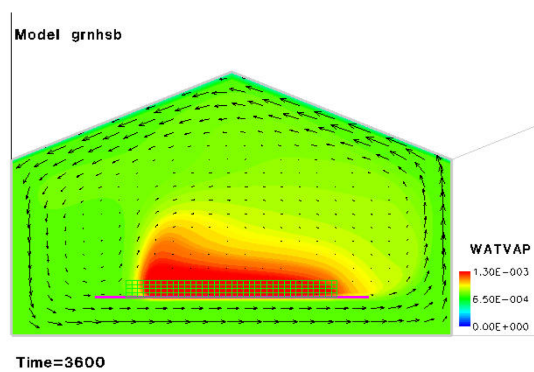


Publication *CAESIM*

A comparable re-circulation flow pattern is seen between the publication and CAESIM simulation results. The velocity magnitude depicted in the publication results seems high (as stated by the author), but the overall comparsion is good.

Water Vapor Fields

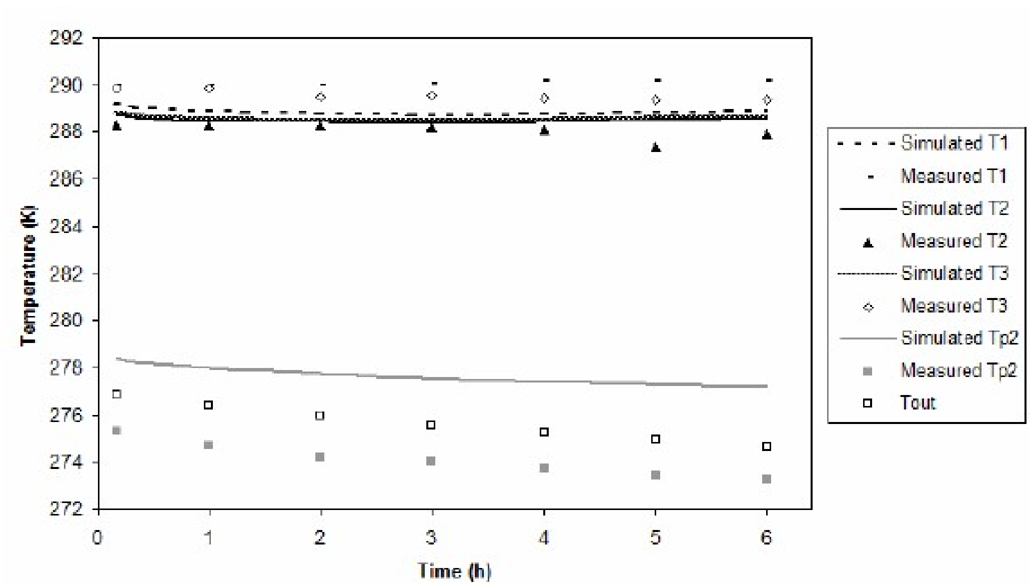


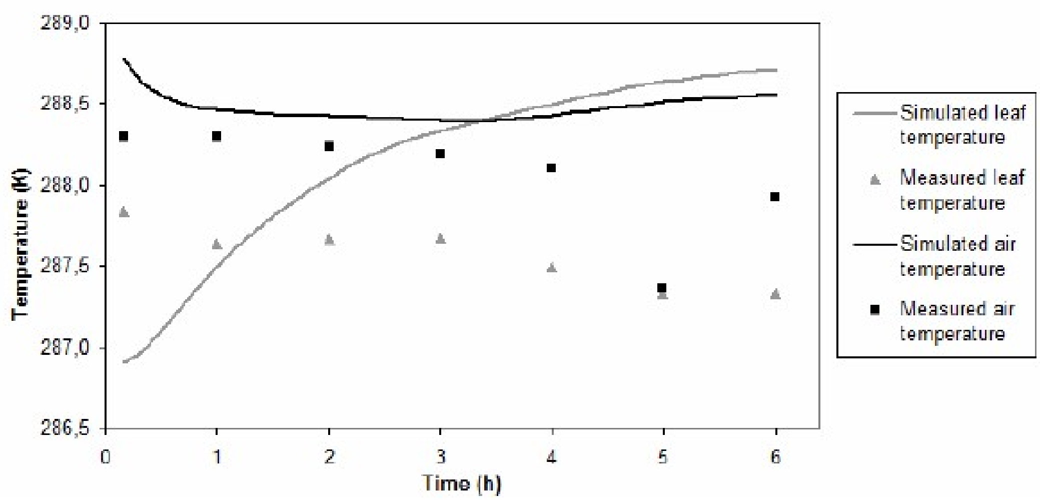


A similar water vapor field is observed between the publication and CAESIM simulation results. The highest concentration of water vapor is located on the plant shelf. Differences observed at the greenhouse boundary walls requires further investigation (difficult with the limited information regarding the numerical approach described in the publication).

Experimental Comparison Analysis

The publication provides two graphs depicting experimentally measured temperatures for greenhouse walls, plant leaf surface, and air. These locations are shown on the experiment schematic (page 6).





Measured temperature values for location T1 (located below plant shelf), average ~ 289.5 K. At the end of the 900 second "grnhsa" simulation, the CAESIM simulated tempeture is 289.53 K. As time progresses, the heat and humidity rises due to the "closed" nature of the system (as noted by the author).

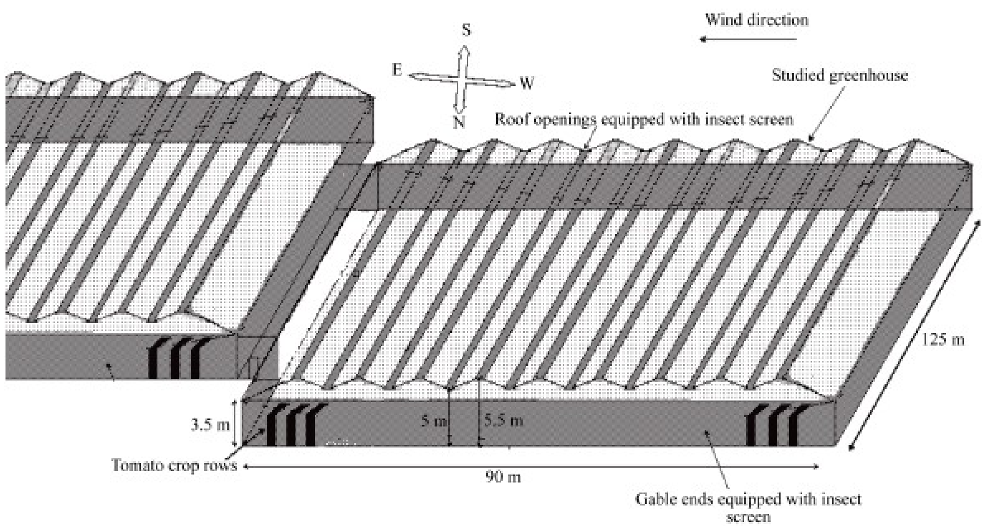
1.0.b Canary Greenhouse CFD Nocturnal Climate Simulation

Case Description

The publication "Canary Greenhouse CFD Nocturnal Climate Simulation", Majdoubi, Boulard et al, Open Journal of Fluid Dynamics, 2016, 6, 88-100. This publication provides details of a numerical and experimental setup to determine the nocturnal climate inside a tomato greenhouse one hectaire in size.

Abstract

The aim of this paper is to predict in details the distributed nocturnal climate inside a one hectare Moroccan canary type tomato-greenhouse equipped with continuous roof and sidewalls ventilation openings with fine insect screens, by means of 3D CFD (Computational Fluid Dynamics) simulations by using a commercial Software package CFD2000 based on the finite volumes method to solve the mass, momentum and energy conservation equations. The turbulent transfers were described by a k-ε model. Likewise, the dynamic influences of insect screens and tomato crop on airflow movement were modeled by means of the concept of porous medium with the Boussinesq assumption. Atmospheric radiations contribution was included in the model by customising the plastic roof cover temperature deducted from its energy balance. Also, the CFD code was customized in order to simulate in each element of the crop cover the sensible and latent heat exchanges between the greenhouse air and tomato crop. Simulations were carried out with a wind prevailing direction perpendicular to the roof openings (west-east direction). Simulations were later validated with respect to temperature and specific humidity field measurements inside the experimental greenhouse. Also, the model was verified respect to global sensible and latent heat transfers. Results show that, generally, greenhouse nocturnal climate distribution is homogeneous along the studies greenhouse area. The insect proof significantly reduced inside airflow wind speed. But there is no significant effect on the inside air temperature and specific humidity respect to outside.



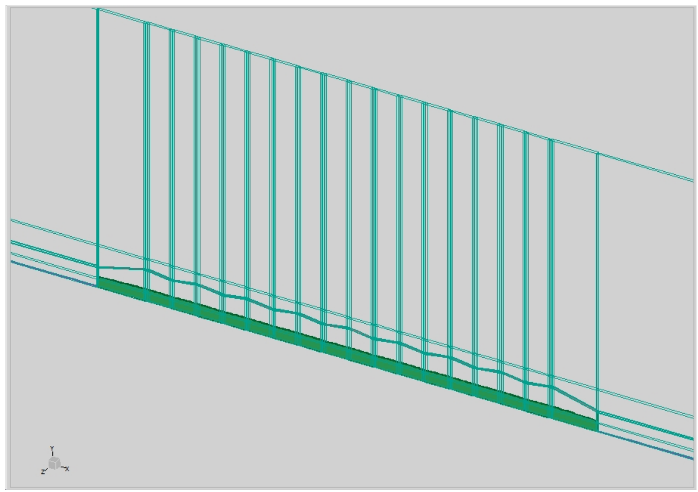
The authors have utilized the CAESIM software, in conjunction with the customization function for a generalized source term, to produce a simulation that models tomato crop transpiration, inclusive of water vapor introduction. The method is similar to the approach developed for this project. A comparison of the simulation results and methodology are presented in this section.

Some assumptions were made in order to best match the physical conditions of the experiment. For example, zero radiation flux is assumed due to the nocturnal time of the experiment. Plant characteristics were set to the same as specified in the publication (i.e., LAI = 3.0).

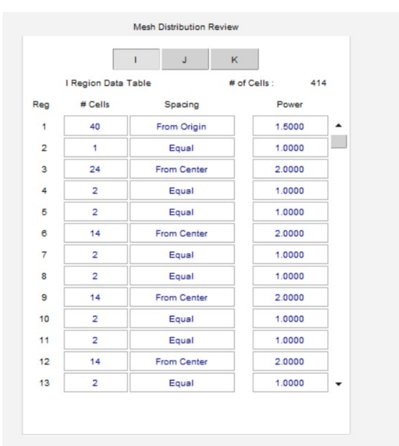
CFD Model Definition

A 2D CFD model was developed to match the physical dimensions and phyics described in the publication. Only a single greenhouse was modeled. A porous media BC was defined for the plant crop. The customized plant transpiration module was activated to allow for plant heat generation and transpiration.

Turbulent flow
Heat transfer activated
Mesh distribution: 414 I 59 J 1 K
1 freestream BC
1 outlet BC
1 wall BCs (ground)
19 porous media BCs (for screens)
1 porous media BC for plant crop
2 customized volumetric source BCs
1 Boussinesq body force BC
1 initialization field BC
Fluid I set to air (rho=1.177 kg/m^3)
Simulation timestep: 0.01 seconds
Tend: 150 seconds (model "boul2da")



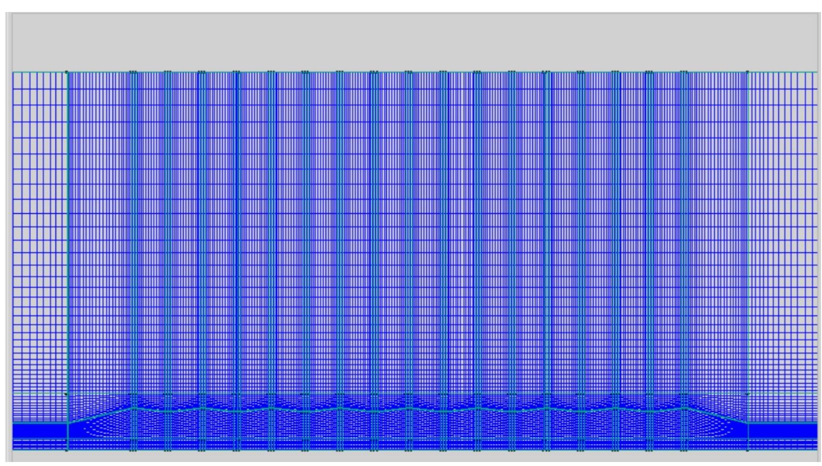
CFD Model " boul2di" - Mesh


Mesh Distribution Review

I J K

I Region Data Table # of Cells : 414

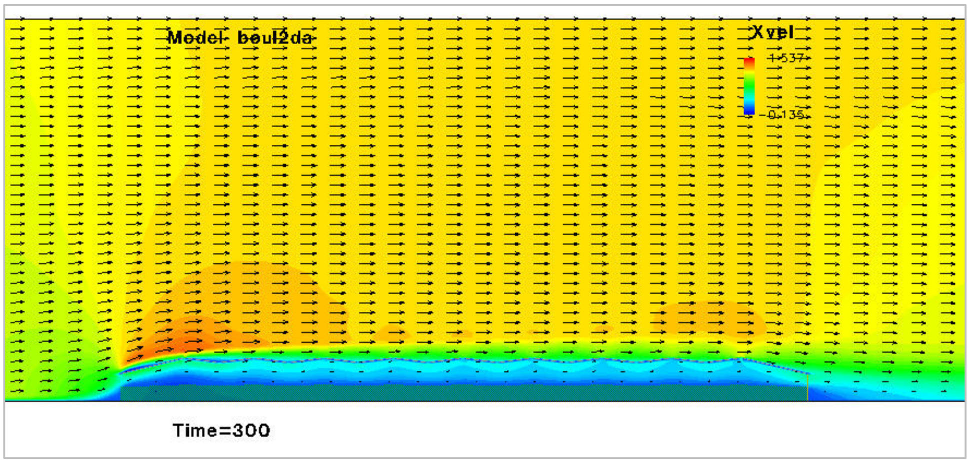
Reg	# Cells	Spacing	Power
1	40	From Origin	1.5000
2	1	Equal	1.0000
3	24	From Center	2.0000
4	2	Equal	1.0000
5	2	Equal	1.0000
6	14	From Center	2.0000
7	2	Equal	1.0000
8	2	Equal	1.0000
9	14	From Center	2.0000
10	2	Equal	1.0000
11	2	Equal	1.0000
12	14	From Center	2.0000
13	2	Equal	1.0000



Note: CFD model "*boul2di*" used to establish a steady-state flow field

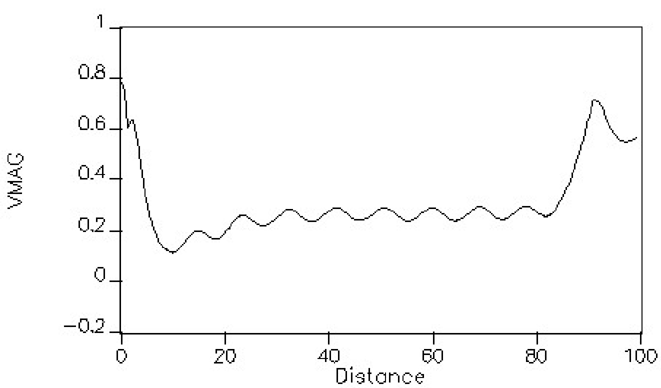
Simulation Results

CFD Model "boul2di" - Velocity Magnitude

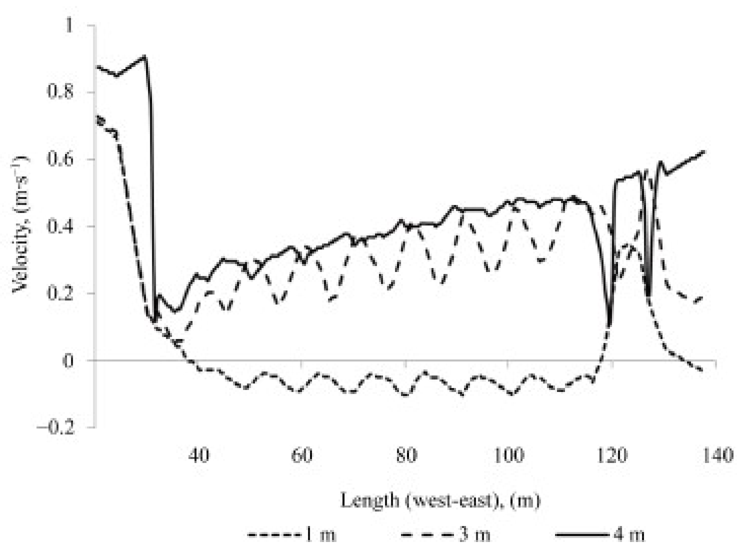


CFD Model "boul2di" - Velocity Magnitude Along Greenhouse (3 m above soil)

CAESIM Result



Publication

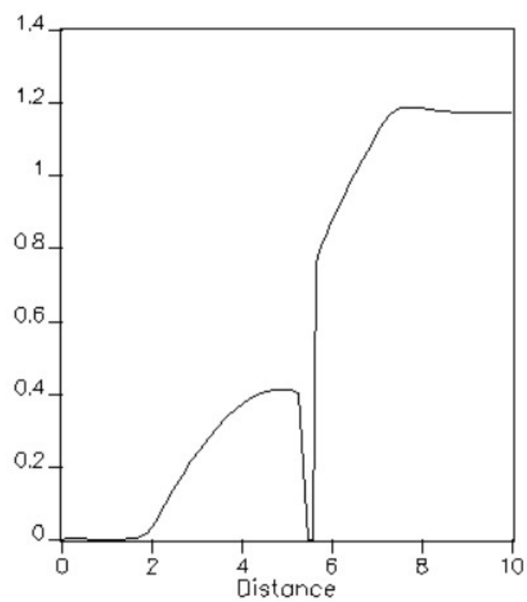


The CAESIM simulation produces a very comparable velocity profile along the length of the greenhouse. The flow characteristics before and after the green house structure are almost identical as shown by the two graphs on the previous page. The publication shows a greater magnitude in the velocity ocscillation and buildup towards the end of the greenhouse.

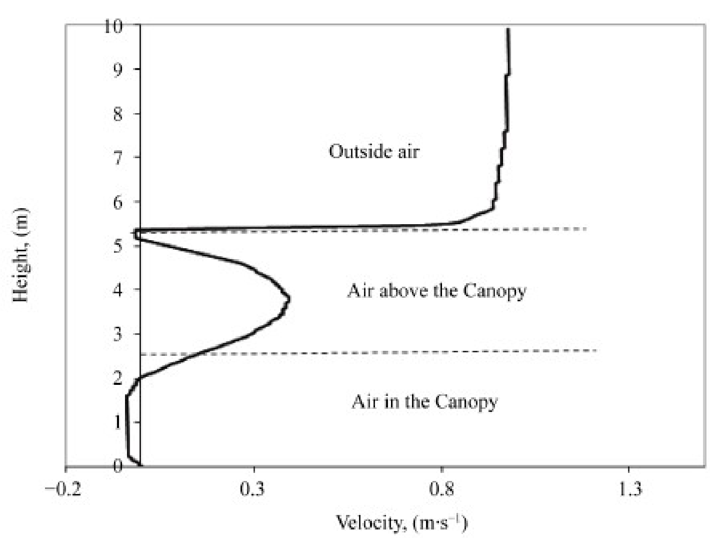
Several development CFD models were executed in order to define reasonable parameters controlling the porous media defined for the screen openings. CFD simulation results are very sensitive to the porous media settings for the screens.

CFD Model "boul2di" – Vertical Velocity Profile at Center of Greenhouse

CAESIM Result



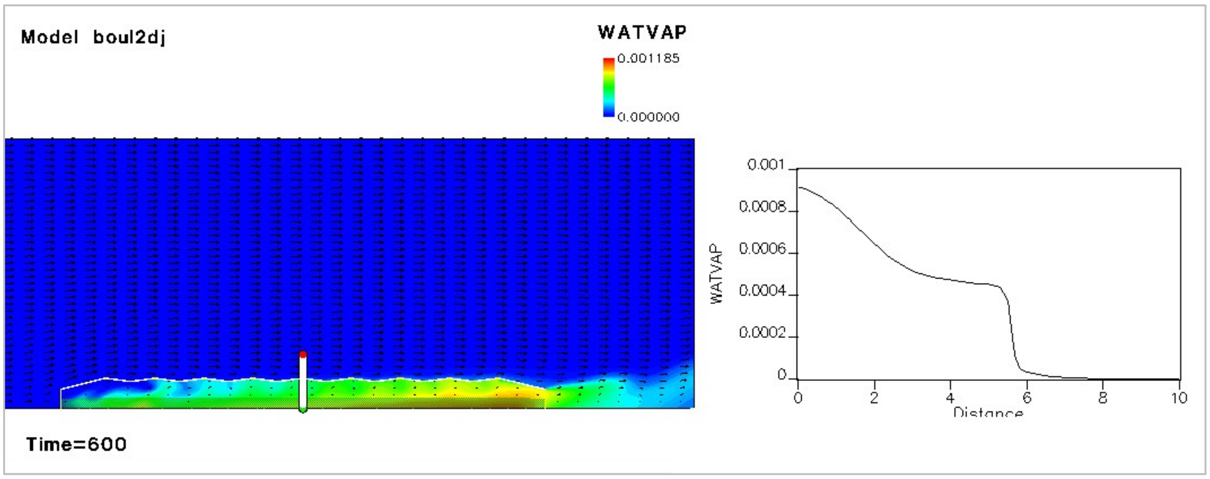
Publication



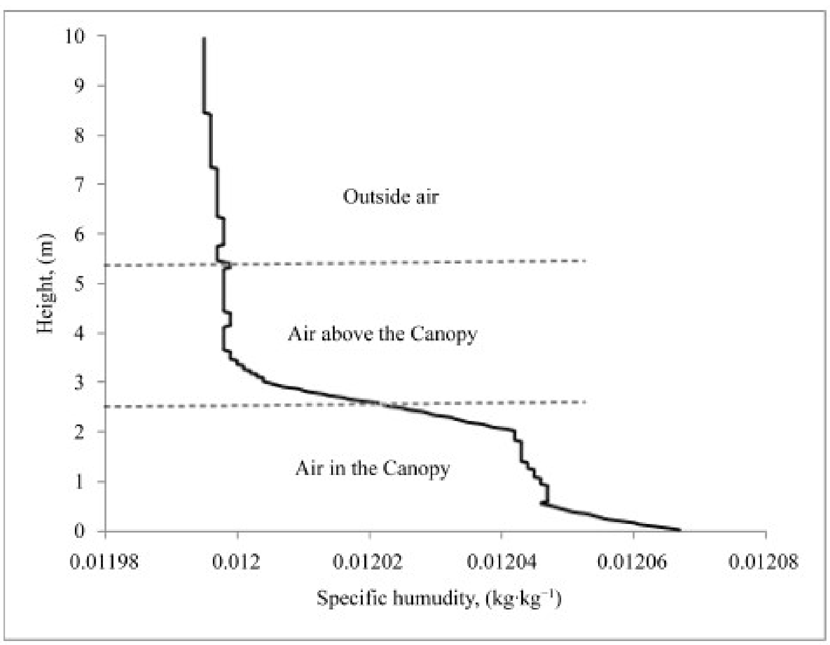
The vertical velocity profiles presented on the previous page show very similar characteristics, where airflow in the crop canopy is minimal, air flow between the crop canopy and roof peaks at the center at ~04 m/s, and air flow above the roof levels off to a fairly constant value. Observed differences are most likely due to CFD setup differences (i.e., mesh discretization and porous media settings).

CFD Model "boul2di" – Vertical Humidity Profile at Center of Greenhouse

CAESIM Result



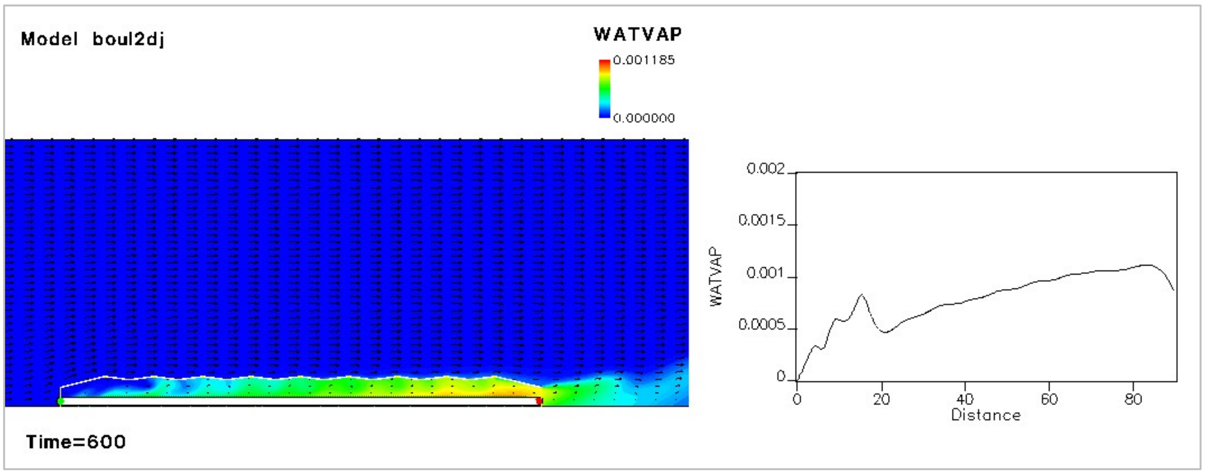
Publication



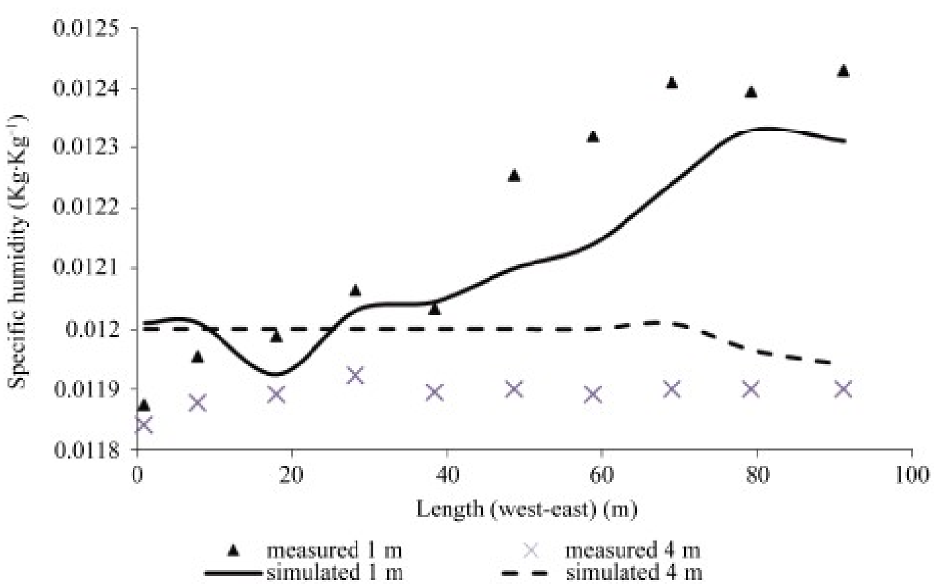
CFD Model "boul2di" – Horizontal Humidity Profile along length of Greenhouse (1 meter height)

The CAESIM simulations shows water vapor concentration increasing along the length of the greenhouse (after 20 meters into the structure). The qualitative trend matches the results from the publication, where the first 20 meters depicts an up water vapor content to be non-linear (due to the re-circulation zone), and then follows a consistent rise along the greenhouse length. Other observed diffences are attributed to general CFD model setup (e.g., porous media BC settings).

CAESIM Result



Publication



Transpiration Modeling Approach

The authors have utilized the CAESIM software to simulate the “Dynamic, Thermal and Hydrous Effects” of a tomato crop cover In a canary greenhouse. They have also customized the STORM flow solver, adding a “volume heat source boundary condition”, which is partitioned into convective and latent heat flux (water vapor).

For modeling the tomato crop, the researchers utilize different definitions for computing aerodynamic resistance and leaf stomatal resistances. The equations used are:

Publication Aerodynmic Resistance Definition - Tamato Crop:

$$r_a = \rho C_p / 0.288\lambda \left(d_v v / \|U\| \right)^{0.5}$$

Aerodynamic Resistance Definition - General

$$r_a = 840\left(\frac{d}{|T_l - T_a|}\right)^{0.25} \quad \text{or} \quad r_a = 220\,\frac{d^{0.2}}{v^{0.8}}$$

Publication Leaf Stomatal Resistance - Tomato Crop:

$$r_s = r_{s_{\min}} \left\{ 1 + 0.11 \exp\left[0.34 \left(6.107 \times 10^{\frac{7.5T_l}{237.5+T_l}} - 1629 w_l - D_{\max} \right) \right] \right\}$$

The radiative flux was considered as not limiting, thus the tomato leaf stomal resistnace was deduced from the temperature and saturation deficit.

Leaf Stomatal Resistance Definition - General

$$r_s = \frac{200(31 + S_g)\,[1 + 0.016*(T_a - 16.4)^2]}{(6.7 + S_g)}$$

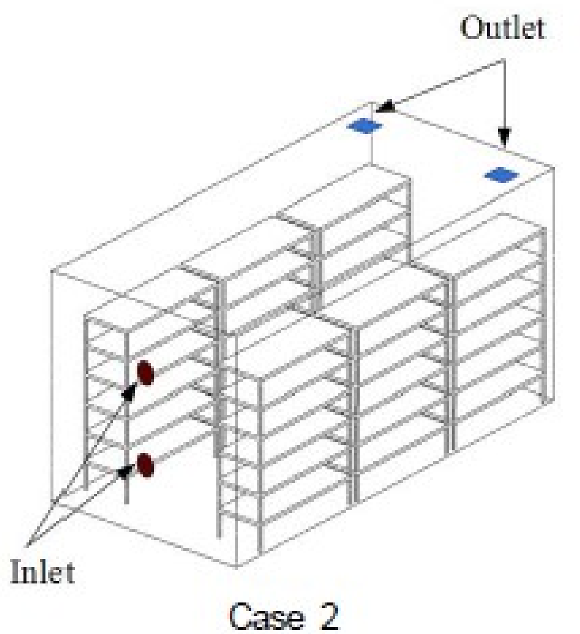
Further research and consideration for the values of aerodynamic and leaf stomatal diffferences is required. A library of values for different plant types is recommended.

1.0.c Analysis of Airflow Pattern in a Plant Factory

Case Description

The publication "Analysis of Airflow Pattern in Plant Factory with Different Inlet and Outlet Locations using Computational Fluid Dynamics", Tae-Gyu Lim and Yong Hyeon Kim, Journal of Biosystems Engineering,39(4):310-317, 2014. This publication provides results of a numerical study showing the effects of inlet/outlet locations on air flow characteristics for a small plant factory.

Purpose: This study was conducted to analyze the air flow characteristics in a plant factory with different inlet and outlet locations using computational fluid dynamics (CFD). **Methods:** In this study, the flow was assumed to be a steady-state, incompressible, and three-dimensional turbulent flow. A realizable k-ε turbulent model was applied to show more reasonable results than the standard model. A CFD software was used to perform the numerical simulation. For validation of the simulation model, a prototype plant factory (5,900 mm x 2,800 mm x 2,400 mm) was constructed with two inlets (Φ250 mm) and one outlet (710 mm x 290 mm), located on the top side wall. For the simulation model, the average air current speed at the inlet was 5.11 m·s^{-1}. Five cases were simulated to predict the airflow pattern in the plant factory with different inlet and outlet locations. **Results:** The root mean square error of measured and simulated air current speeds was 13%. The error was attributed to the assumptions applied to mathematical modelling and to the magnitude of the air current speed measured at the inlet. However, the measured and predicted airflow distributions of the plant factory exhibited similar patterns. When the inlets were located at the center of the side wall, the average air current speed in the plant factory was increased but the spatial uniformity was lowered. In contrast, if the inlets were located on the ceiling, the average air current speed was lowered but the uniformity was improved. **Conclusions:** Based on the results of this study, it was concluded that the airflow pattern in the plant factory with multilayer cultivation shelves was greatly affected by the locations of the inlet and the outlet.



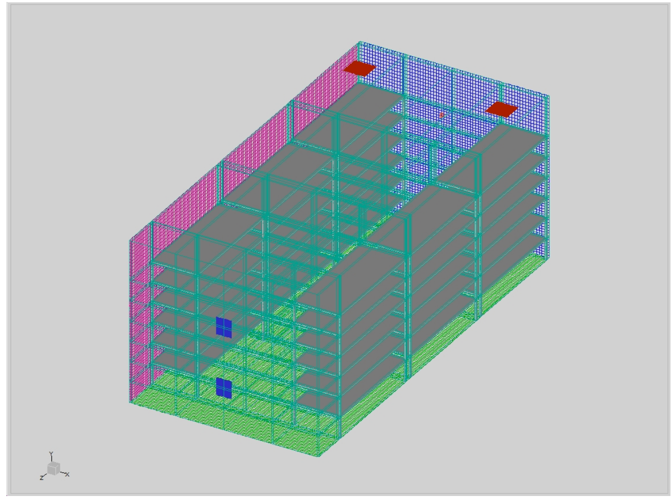
Geometric model for Case 2

Case 2 was selected for the comparsison. Two CAESIM simulations will be executed, one with and one without plant definitions. This will provide insight as to the impact of air re-circulation due to the plant shelves being populated with plants.

CFD Model Definition

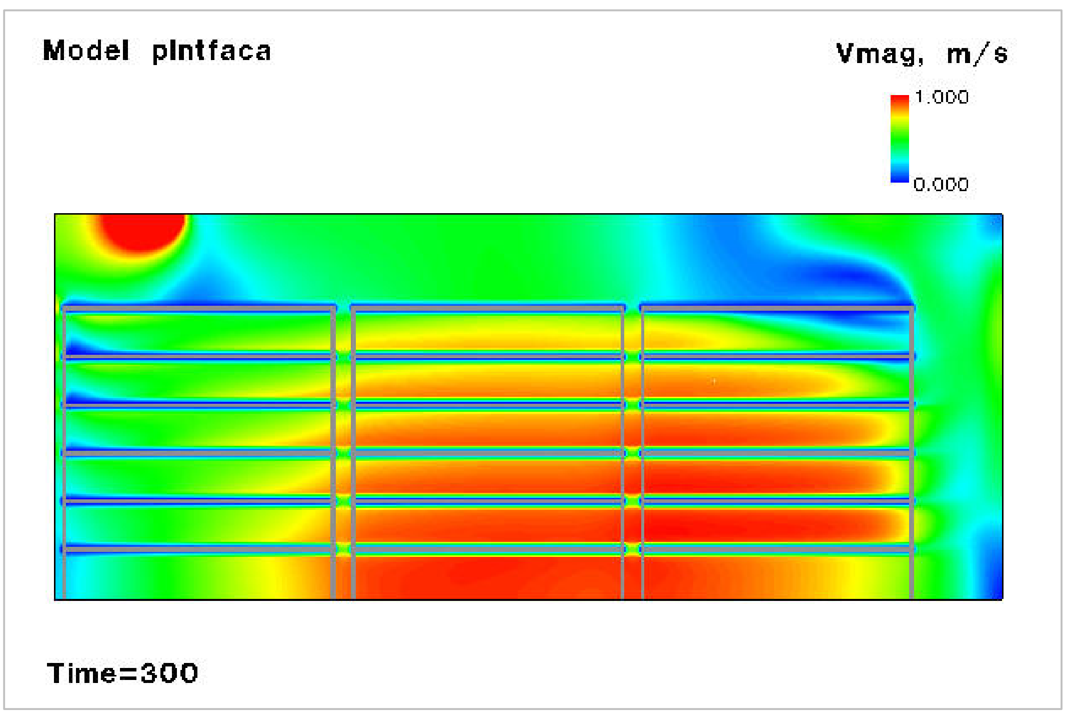
A 3D CFD model was developed to match the physical dimensions and phyics described in the publication.

Turbulent flow
Heat transfer activated
Mesh distribution: 72 I 61 J 178 K
2 inlet BC
2 outlet BC
180 blockage BCs
Fluid I set to air (rho=1.177 kg/m^3)
Simulation timestep: 0.025 seconds
Tend: 300 seconds (model "plntfaca")



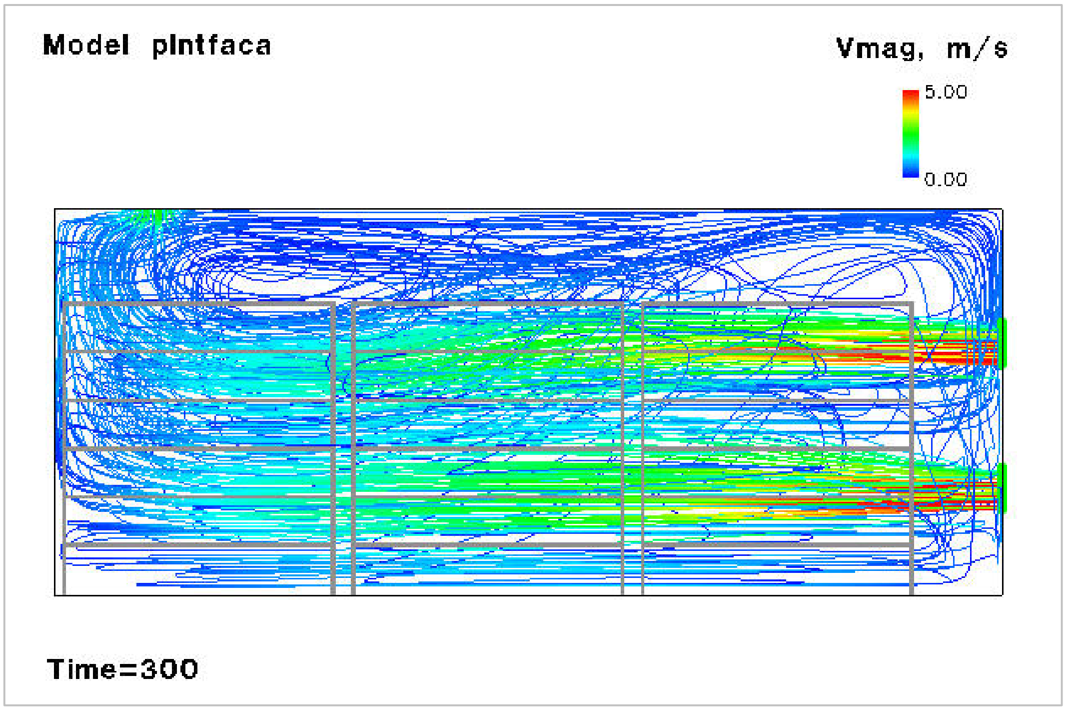
Simulation Results

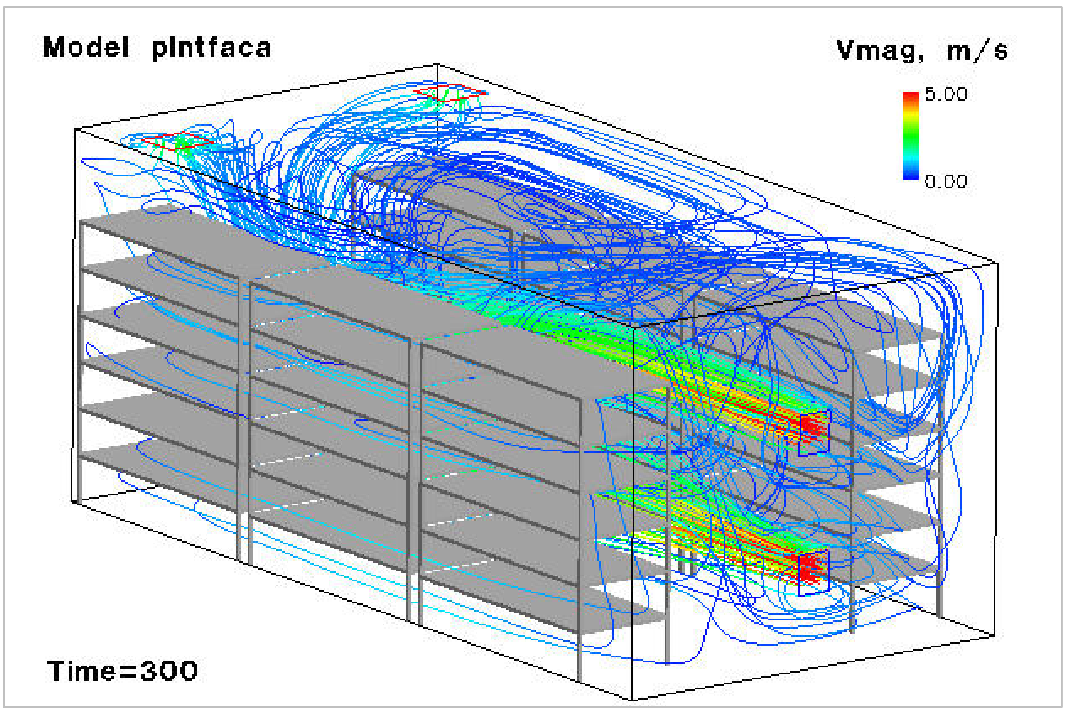
CFD Model " plntfaca" - Velocity Magnitude



Plane location at shelf center

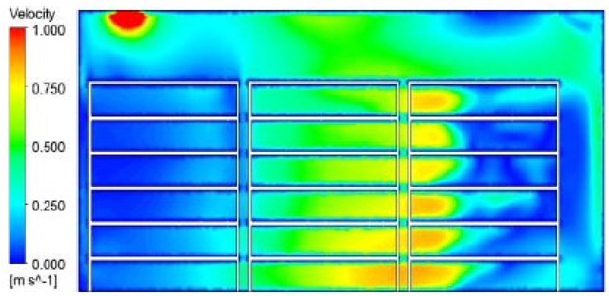
CFD Model " plntfaca" - Flow Streamlines



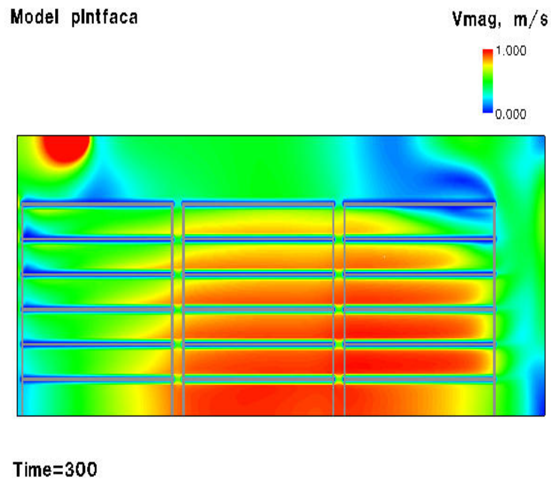


Numerical Comparison Analysis

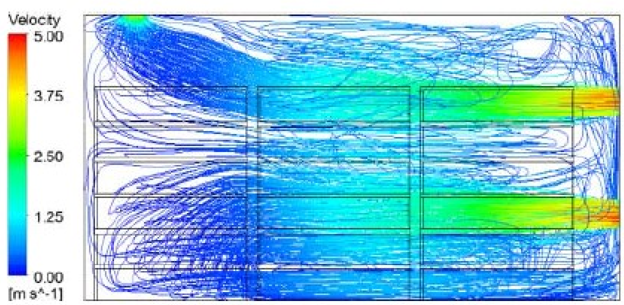
Velocity Magnitude



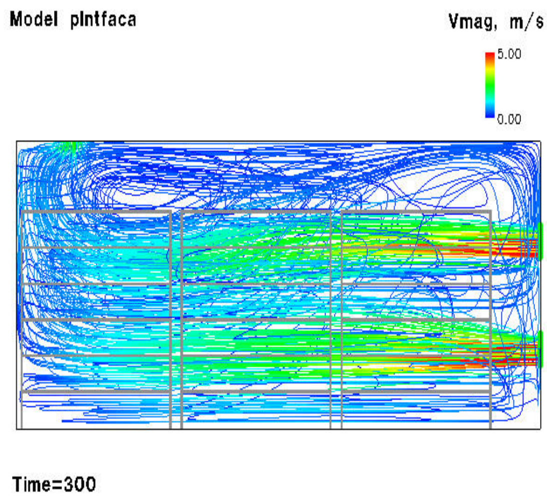
Publication



CAESIM



Publication

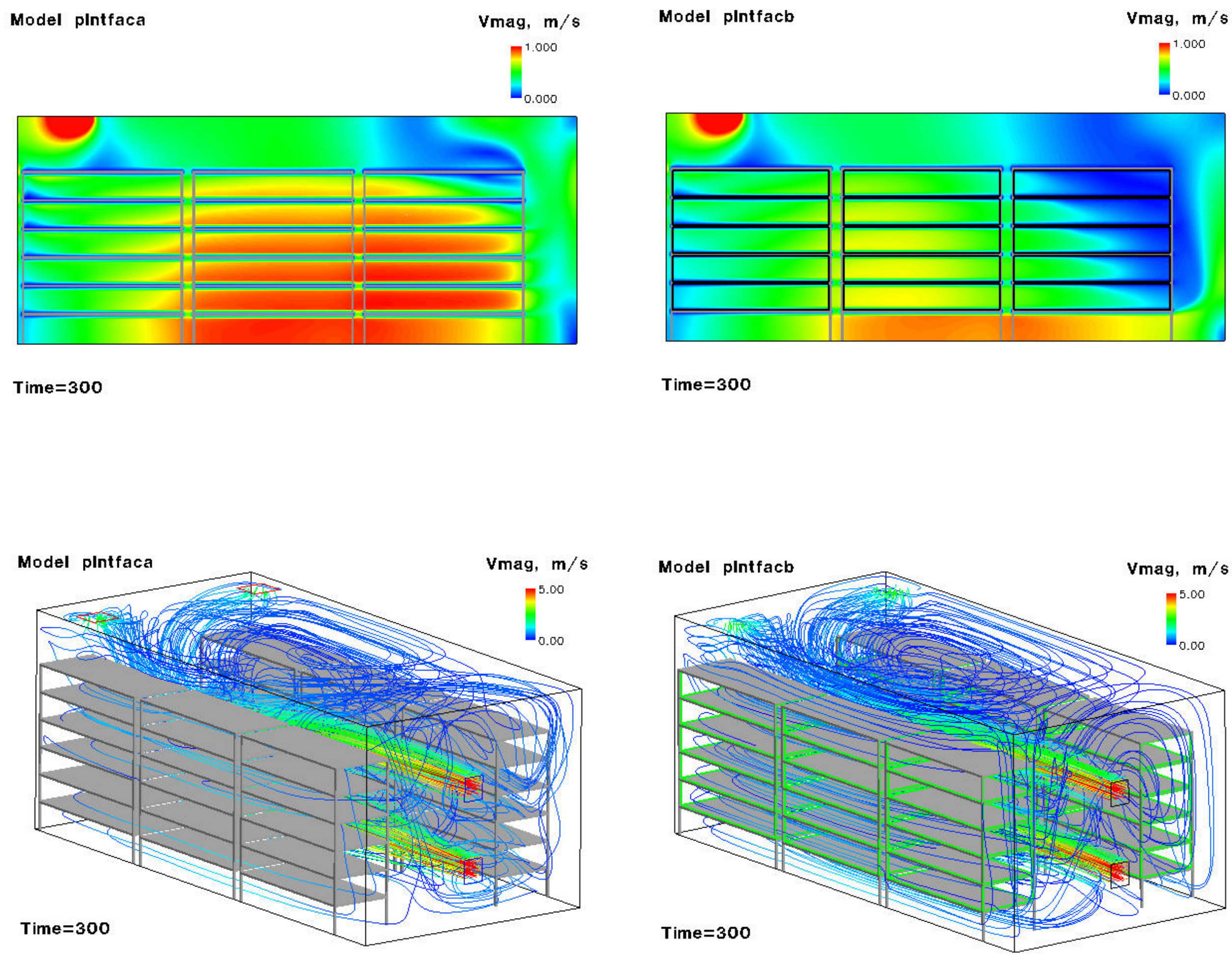


CAESIM

Comparable flow fields are observed between publication and CAESIM simulation results. There are some slight differences between the CFD models that could account for the observed flow field variation (e.g., inlets slightly lower in CAESIM model which splits the incoming flow between two shelf levels).

The paper concluded "that the airflow pattern in the plant factory with multilayer cultivation shelves was greatly affected by the locations of the inlet and outets". It should be noted, however, that the publication research does not take into account the presence of any plants in the factory. A second CAESIM model was generated that introduced plants on each shelving unit (using porous media boundary conditions similar to that used for Basil). The results are shown next

CFD Models " plntfaca" and "plntfacb" - Velocity Magnitude



It is clear that the presence of plants in the factory has a significant impact to the air flow patterns (and magnitude) within the shelving units. This will in turn have a significant effect on humidity distributions with the factory as well. Further research is required modeling medium to large plant factory sized environments that include all physics being simulated.

2.0 Parametric 3D CFD Simulations

A set of 3D simulations have been defined and executed that allows for a qualitative and quatitative comparitive analysis related to plant vapor production. Section 4.0 presents simulation results for a matrix of 8 3D CFD model simulations specifying 1) two plant types, 2) 2 plant densities, and 3) 2 temperature differences. The table below summarizes the 3D CFD simulations.

RUN #	MODEL NAME	PLANT	DENSITY	TEMP
1	arlodena	arugula	low	mid
2	arlodenb	arugula	low	high
3	arhidena	arugula	high	mid
4	arhidenb	arugula	high	high
5	balodena	basil	low	mid
6	balodenb	basil	low	high
7	bahidena	basil	high	mid
8	bahidenb	basil	high	high

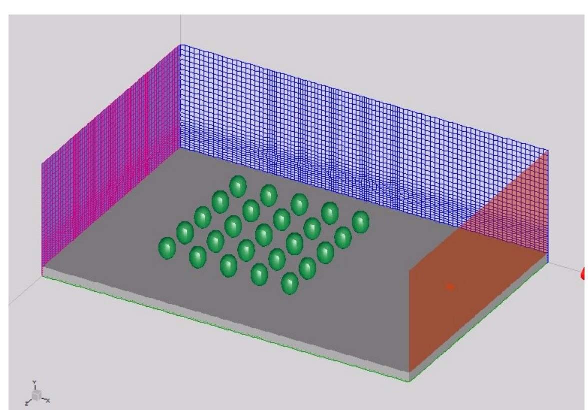
Note that "high" DENSITY means 100 arugula plants or 100 basil plants, and "low" DENSITY means 25 arugula or 25 basil plants. Also, "high" TEMP means a 100% higher temperature differential between leaf and air (locally).

2.0.a Arugula Simulations

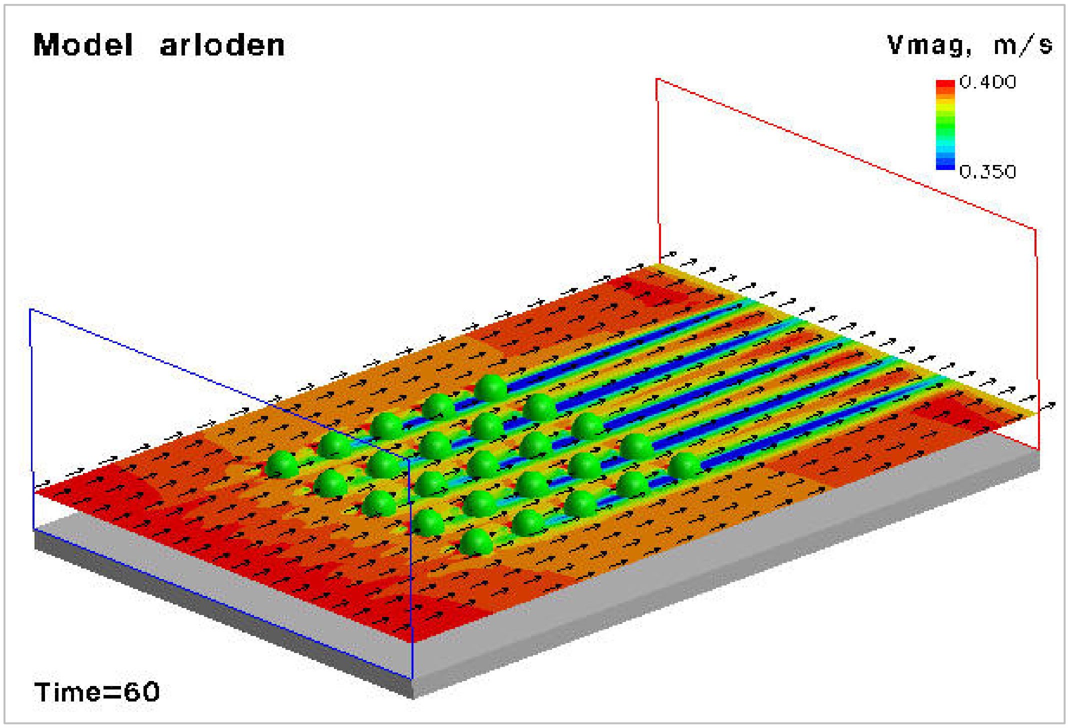
Two CFD models ares executed to generate the preliminary flow field solution restarts for both the "low" and "high" density plant scenarios. Subsequently, two (2) simulations are then executed for both scenarios varying temperature difference between plant leaf and air.

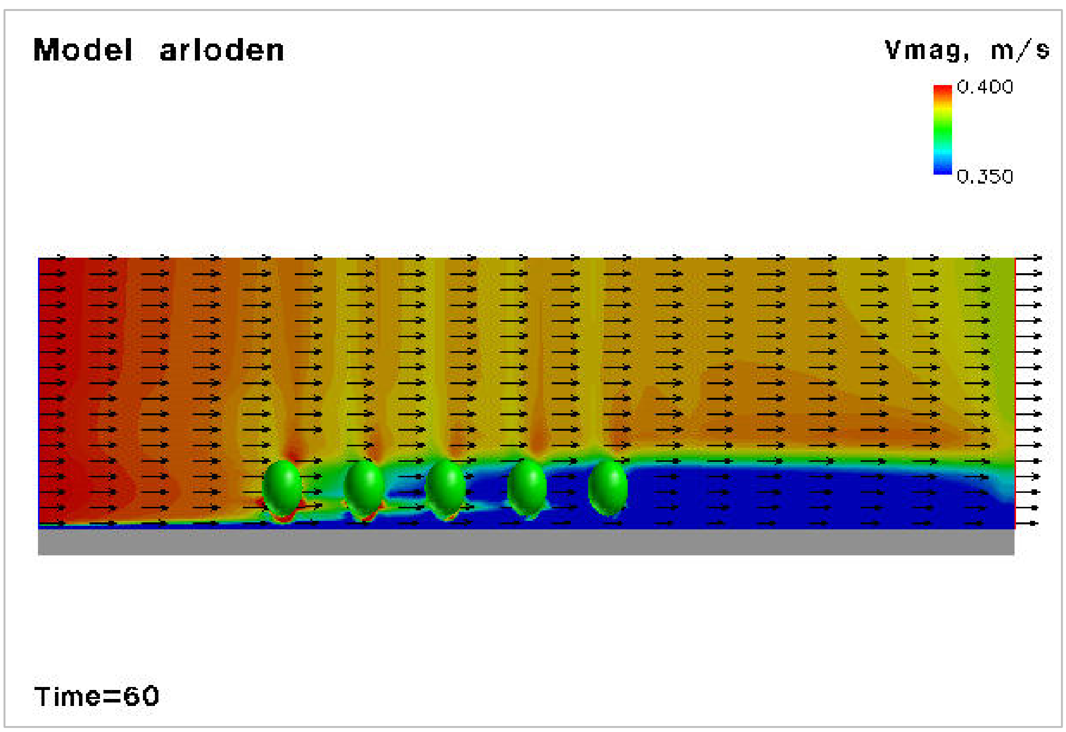
"Low" DENSITY CFD Model Definition ("arloden")

Turbulent flow
Heat transfer activated
Mesh distribution: 96 I 32 J 68 K
1 inlet BC
1 outlet BC
25 porous media BCs
Fluid I set to air (rho=1.177 kg/m^3)
Simulation timestep: 0.05 seconds
Tend: 60 second



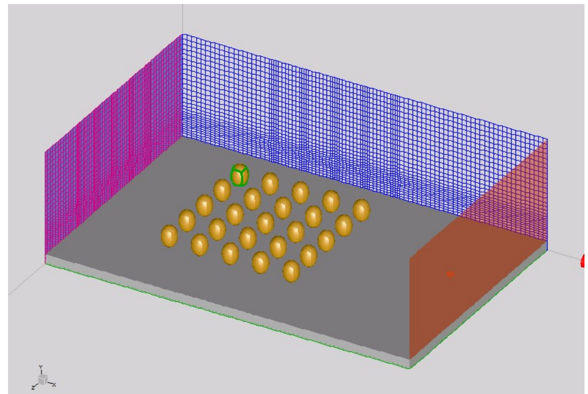
Model* "arloden" *- Velocity Magnitude





"Low" DENSITY CFD Model Definition ("arlodena")

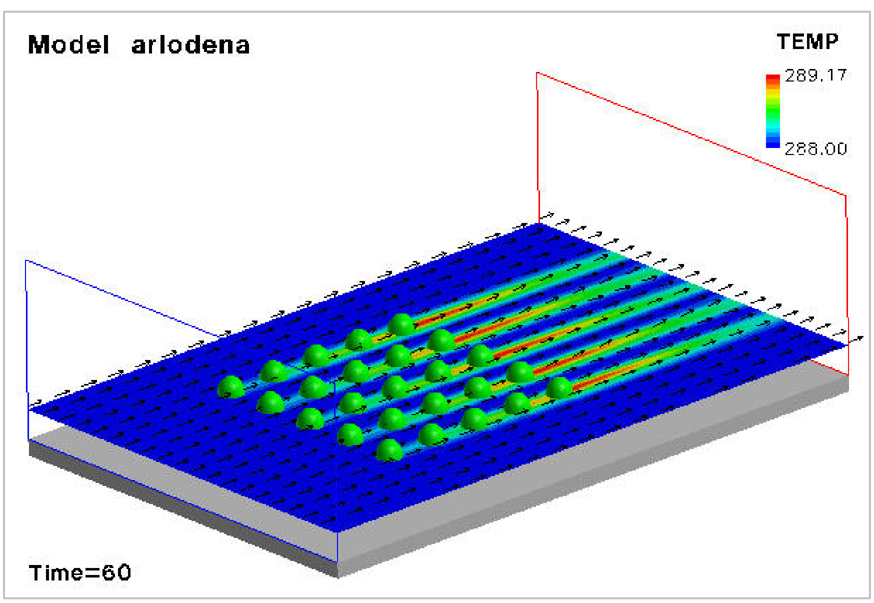
Turbulent flow
Heat transfer activated
Mesh distribution: 96 I 32 J 68 K
1 inlet BC
1 outlet BC
25 porous media BCs
50 source BCs
Fluid I set to air (rho=1.177 kg/m^3)
Simulation timestep: 0.05 seconds
Tend: 60 second



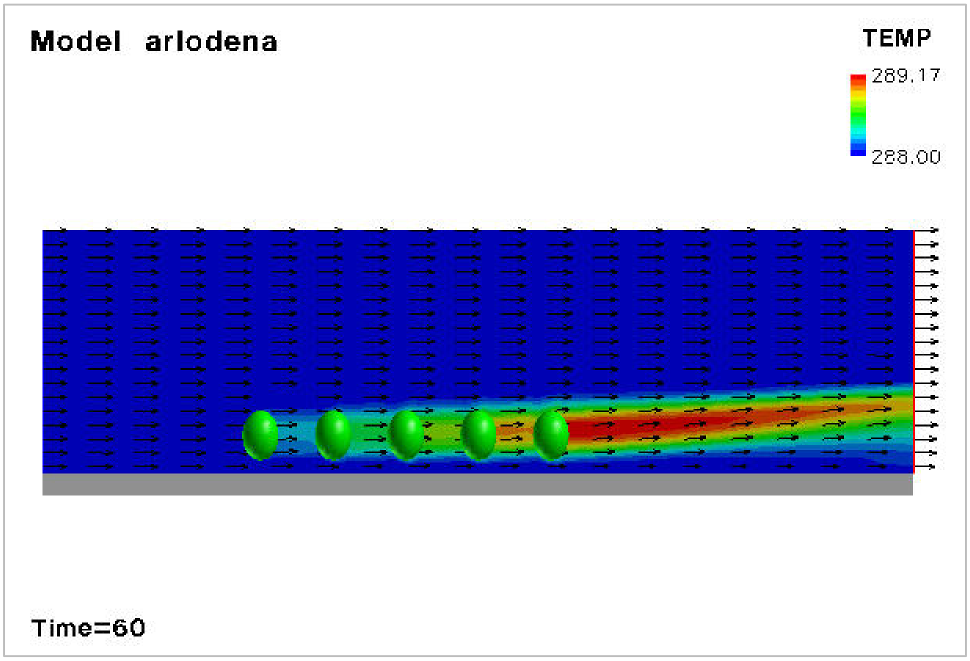
Model "arlodena" - Transpiration Input

```
arlodena_trinp - Notepad
File  Edit  Format  View  Help
1              ! ier2        1=on   0=off
2              ! number of plant species
4.0 4.0        ! leaf index
0.04 0.04      ! leaf characteristic length m
0.02 0.02      ! humidity of leaf           kg/kg
0.2            ! coefficient
270.0          ! radiation source           W/m^2
288.00         ! air temperature            K
0.0190         ! humidity of air            kg/kg
2.27e6         ! latent heat of water vap   J/kg
1004.0         ! specific heat of air       J/kg-K
10             ! print frequency
```

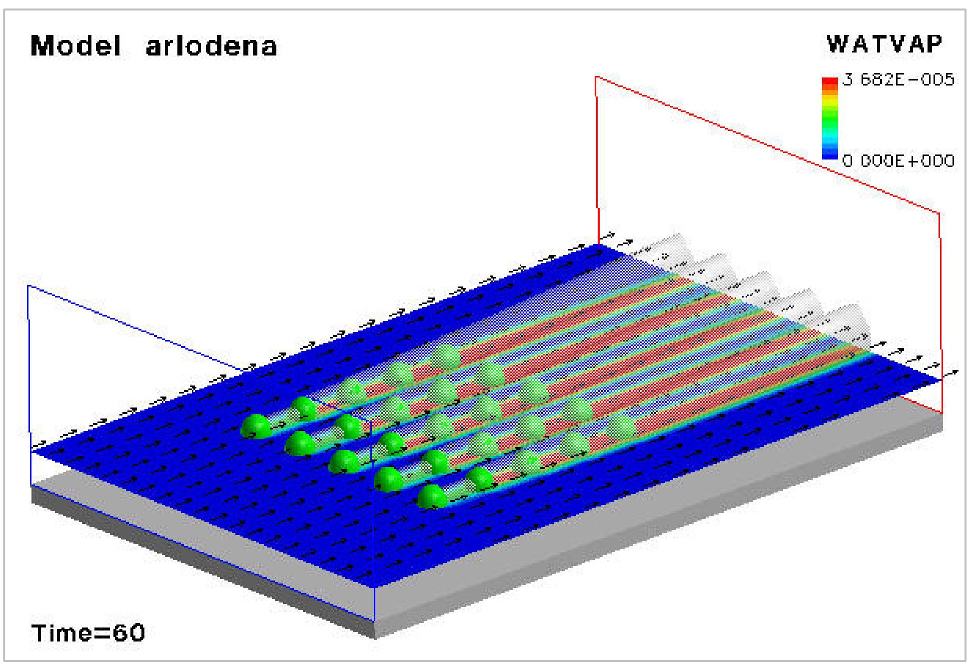
Model "arlodena" - Temperature Field Iso-View



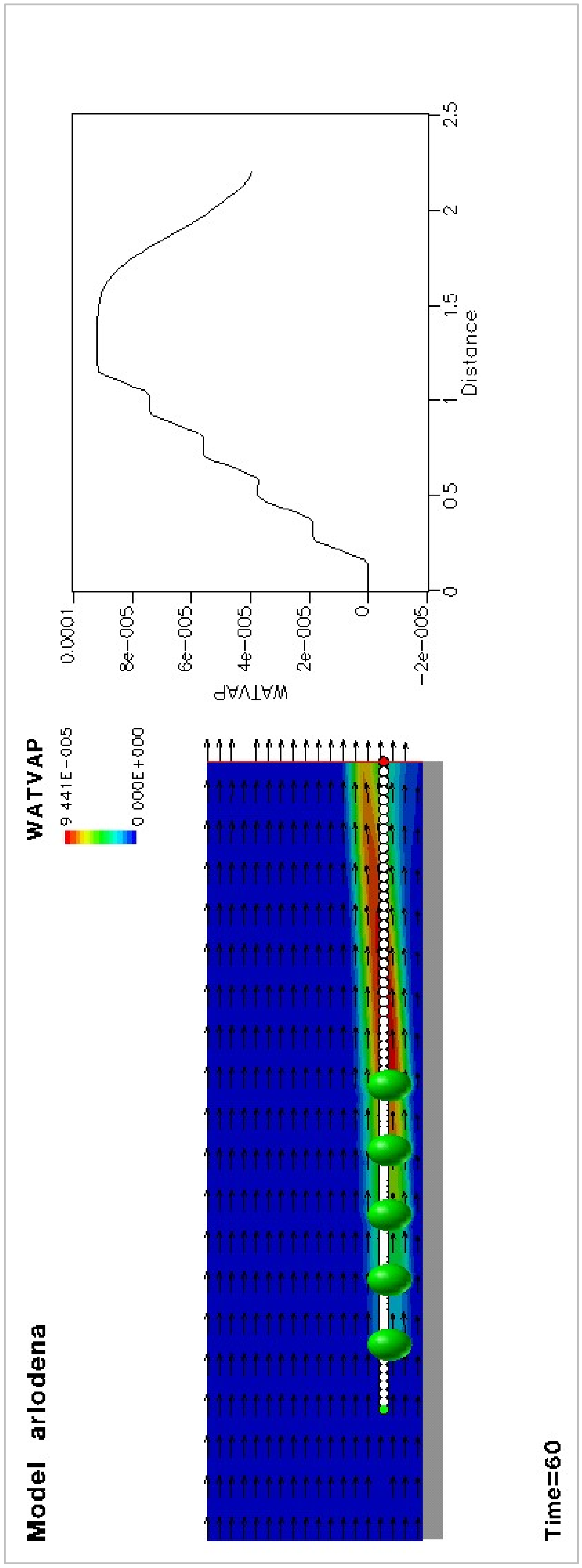
Model "arlodena" - Temperature Field Side View



Model "arlodena" - Water Vapor Field Iso-View

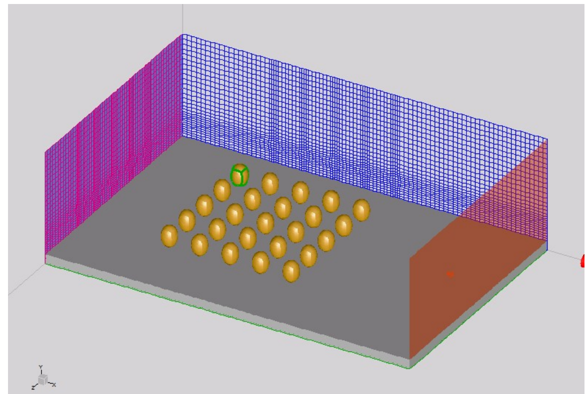


Model “*arlodena*” - Water Vapor Field Side View

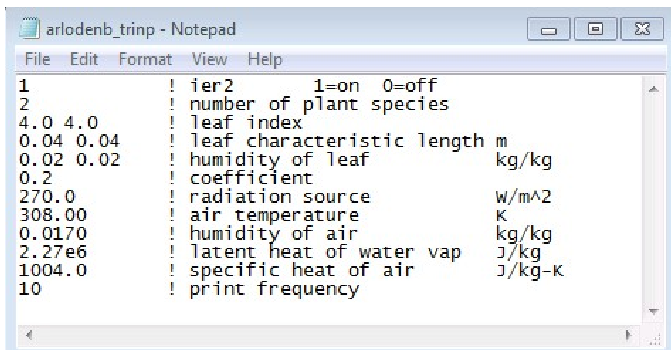


"Low" DENSITY CFD Model Definition ("arlodenb")

Turbulent flow
Heat transfer activated
Mesh distribution: 96 I 32 J 68 K
1 inlet BC
1 outlet BC
25 porous media BCs
50 source BCs
Fluid I set to air (rho=1.177 kg/m^3)
Simulation timestep: 0.05 seconds
Tend: 60 second



Model "arlodenb" - Transpiration Input

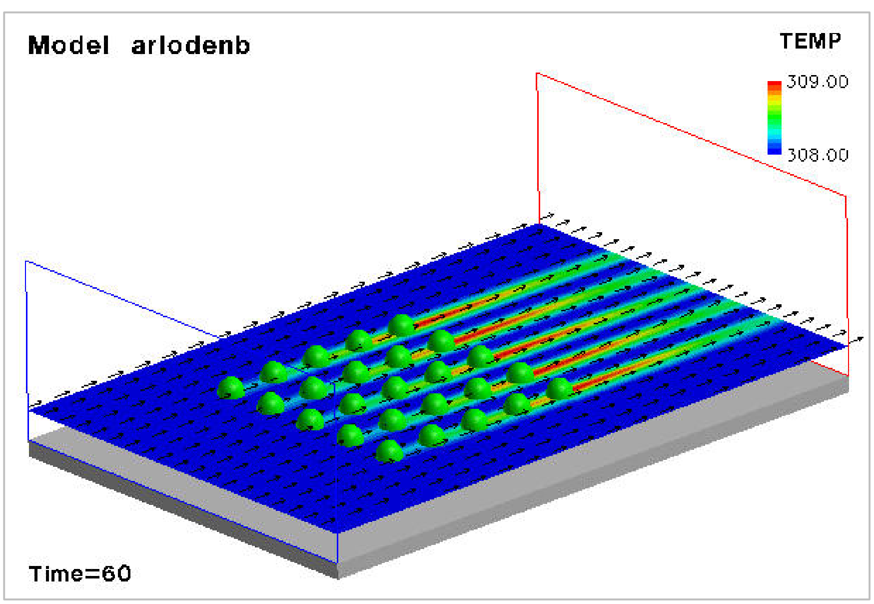


arlodenb_trinp - Notepad

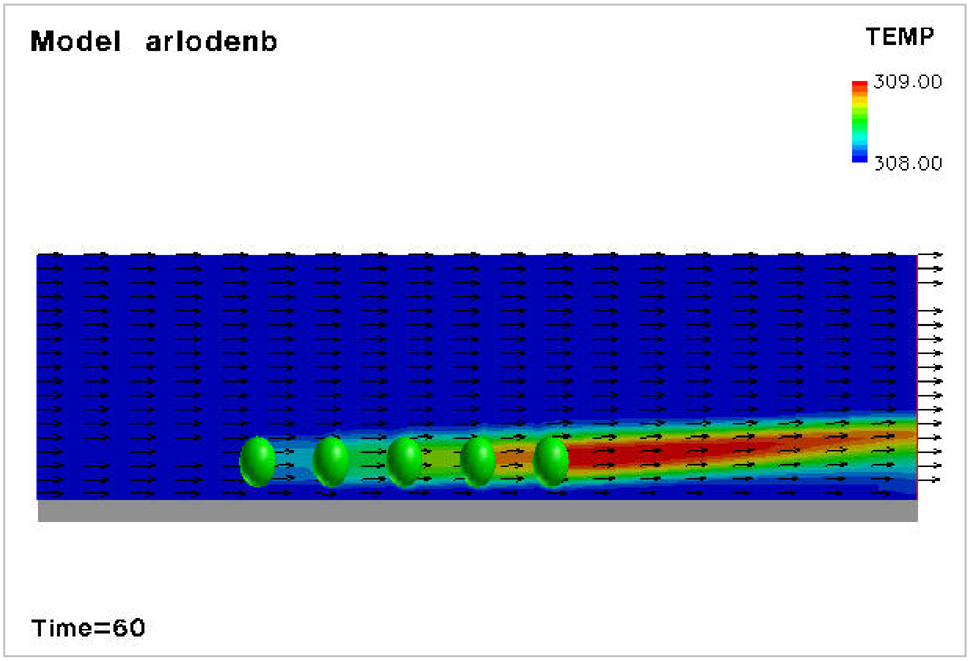
File Edit Format View Help

```
1               ! ier2        1=on   0=off
2               ! number of plant species
4.0 4.0         ! leaf index
0.04 0.04       ! leaf characteristic length m
0.02 0.02       ! humidity of leaf           kg/kg
0.2             ! coefficient
270.0           ! radiation source           W/m^2
308.00          ! air temperature            K
0.0170          ! humidity of air            kg/kg
2.27e6          ! latent heat of water vap   J/kg
1004.0          ! specific heat of air       J/kg-K
10              ! print frequency
```

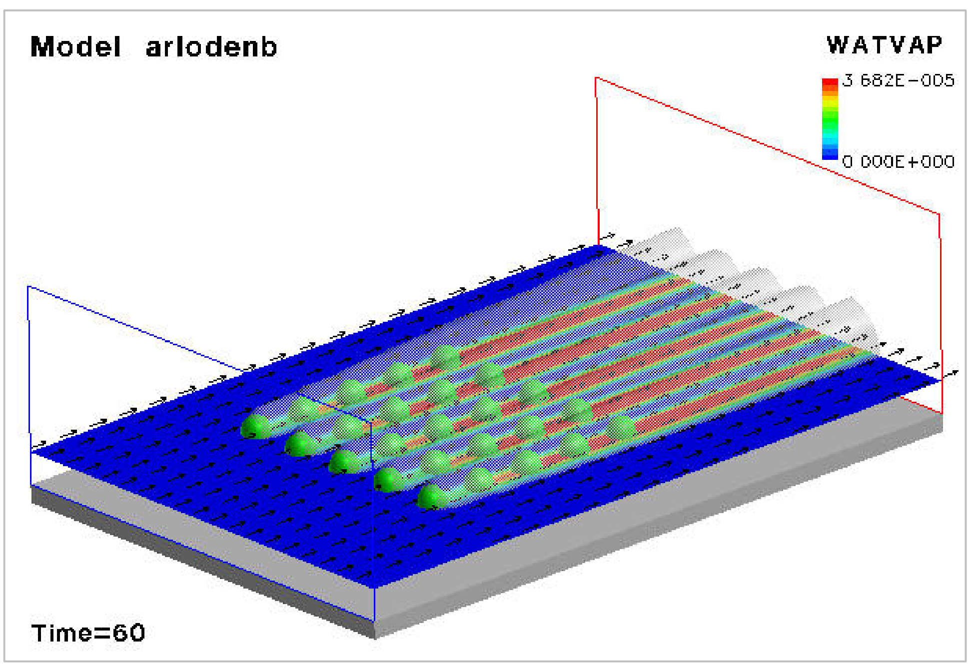
Model "arlodenb" - Temperature Field Iso-View



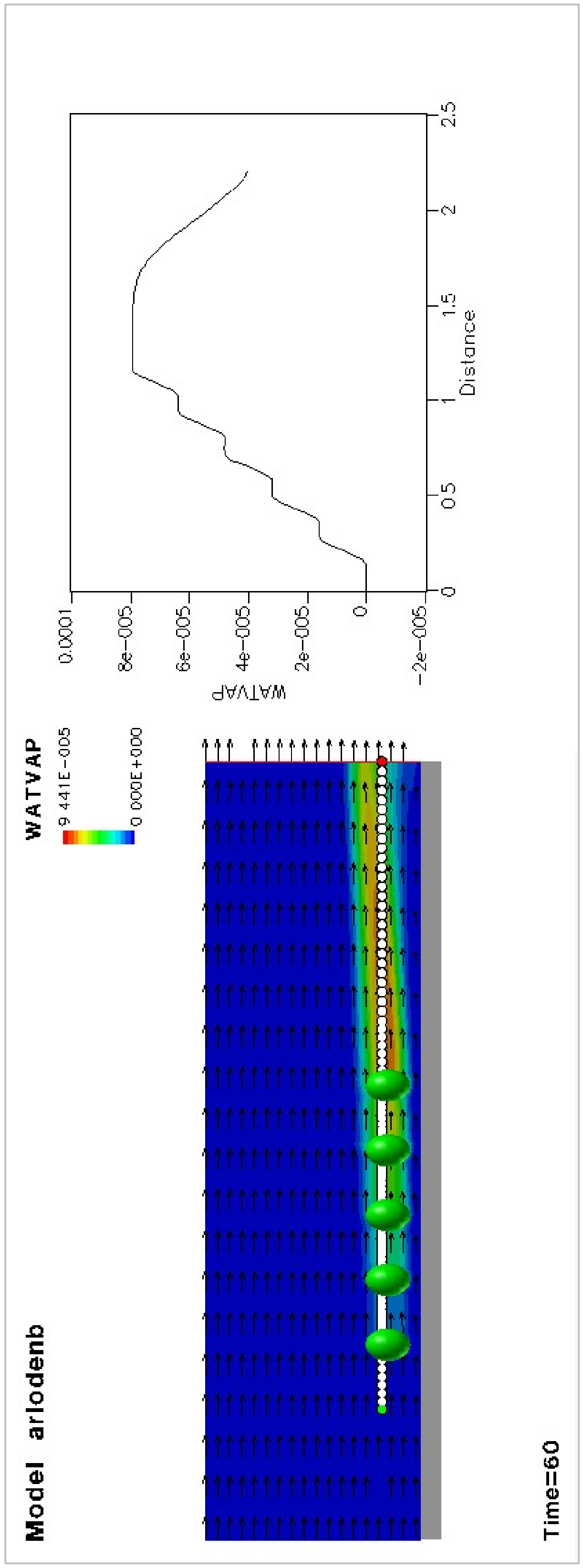
Model "arlodenb" - Temperature Field Side View



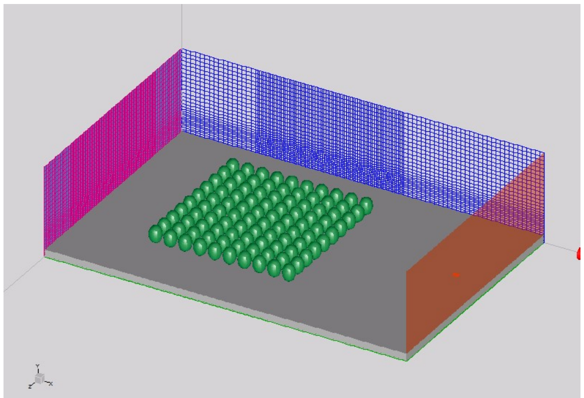
Model "arlodenb" - Water Vapor Field Iso-View



Model "*arlodena*" - Water Vapor Field Side View

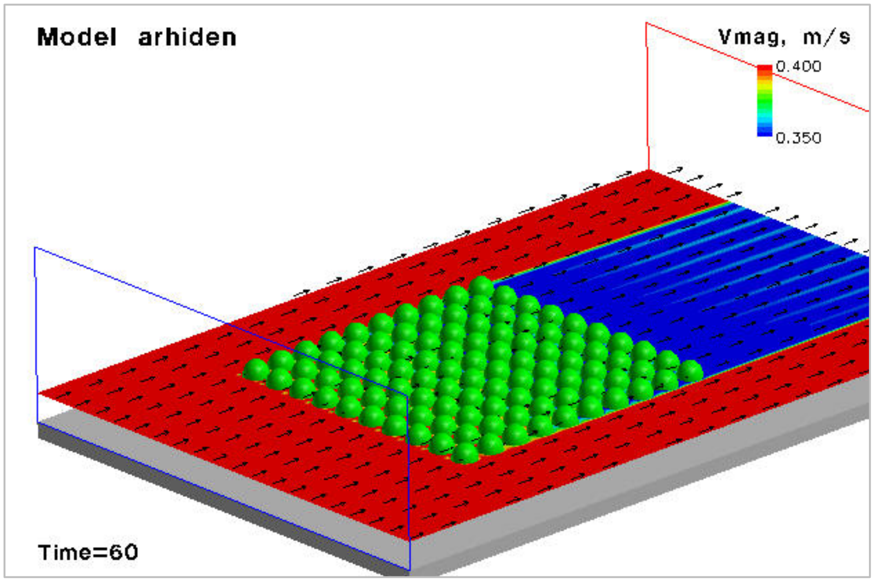


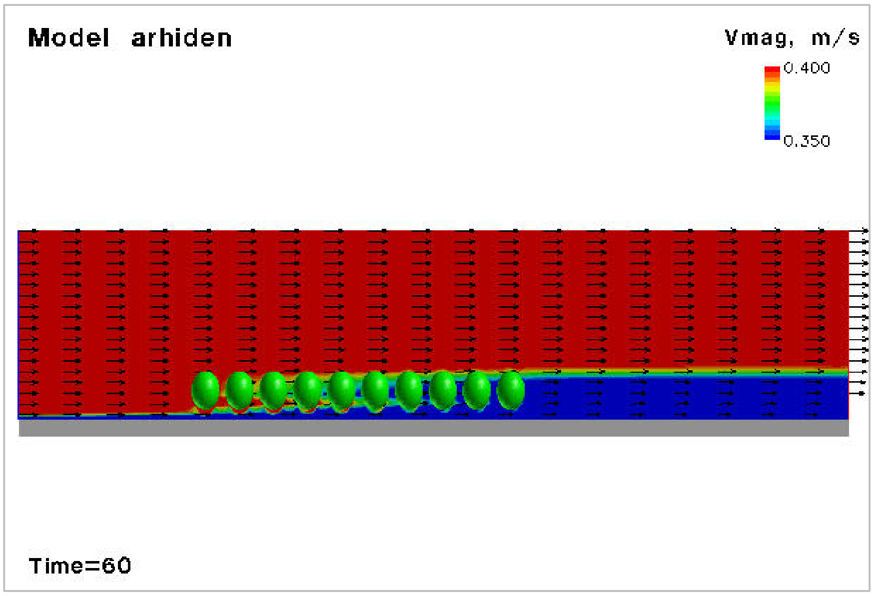
"High" DENSITY CFD Model Definition



Turbulent flow
Heat transfer activated
Mesh distribution: 128 I 32 J 106 K
1 inlet BC
1 outlet BC
100 porous media BCs
Fluid I set to air (rho=1.177 kg/m^3)
Simulation timestep: 0.05 seconds
Tend: 60 seconds (model "arloden")

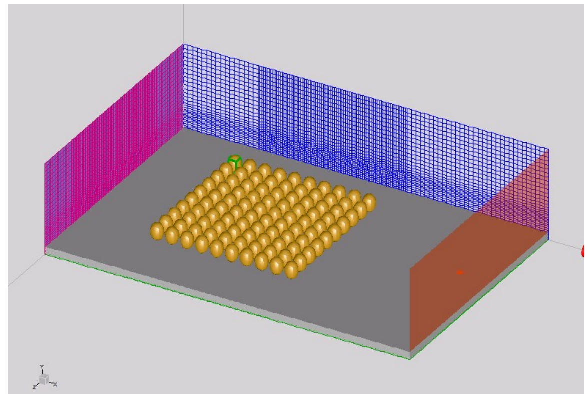
Model "arhiden" - Velocity Magnitude



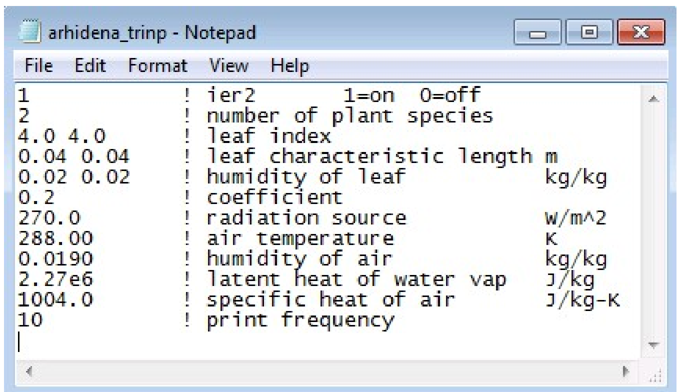


"High" DENSITY CFD Model Definition ("arhidena")

Turbulent flow
Heat transfer activated
Mesh distribution: 128 I 32 J 106 K
1 inlet BC
1 outlet BC
100 porous media BCs
200 source BCs
Fluid I set to air (rho=1.177 kg/m^3)
Simulation timestep: 0.05 seconds
Tend: 60 second

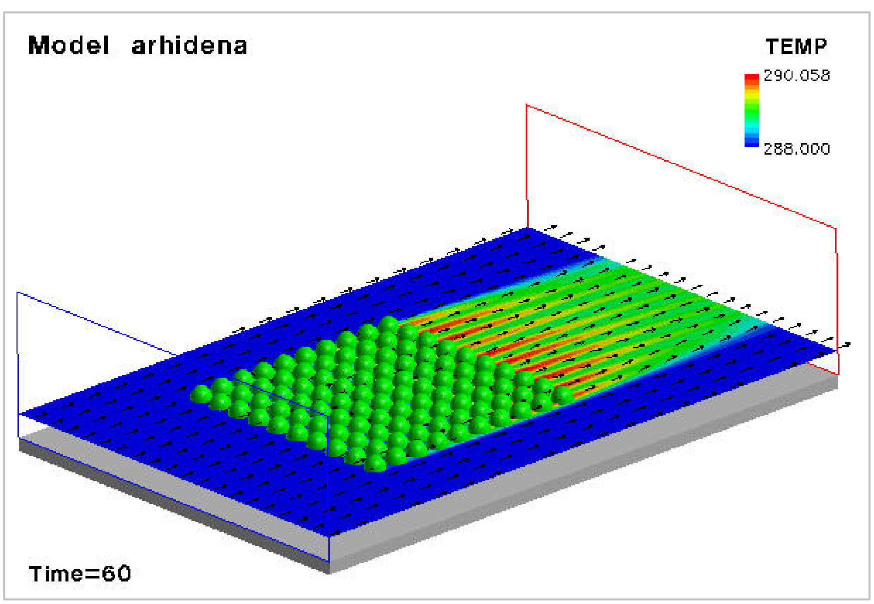


Model "arhidena" - Transpiration Input

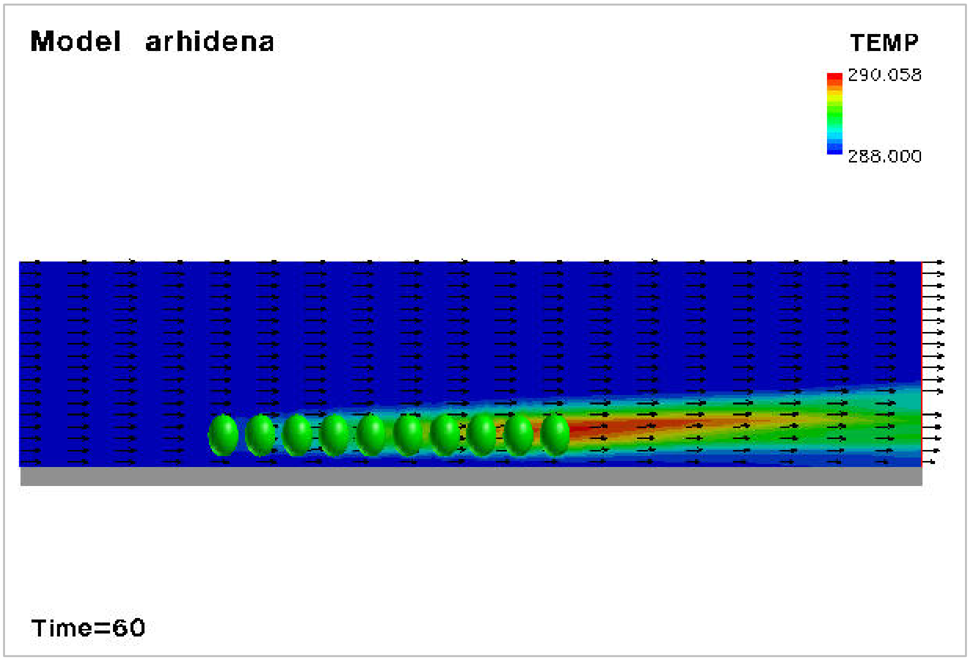



```
1              ! ier2        1=on  0=off
2              ! number of plant species
4.0 4.0        ! leaf index
0.04 0.04      ! leaf characteristic length m
0.02 0.02      ! humidity of leaf          kg/kg
0.2            ! coefficient
270.0          ! radiation source          W/m^2
288.00         ! air temperature           K
0.0190         ! humidity of air           kg/kg
2.27e6         ! latent heat of water vap  J/kg
1004.0         ! specific heat of air      J/kg-K
10             ! print frequency
```

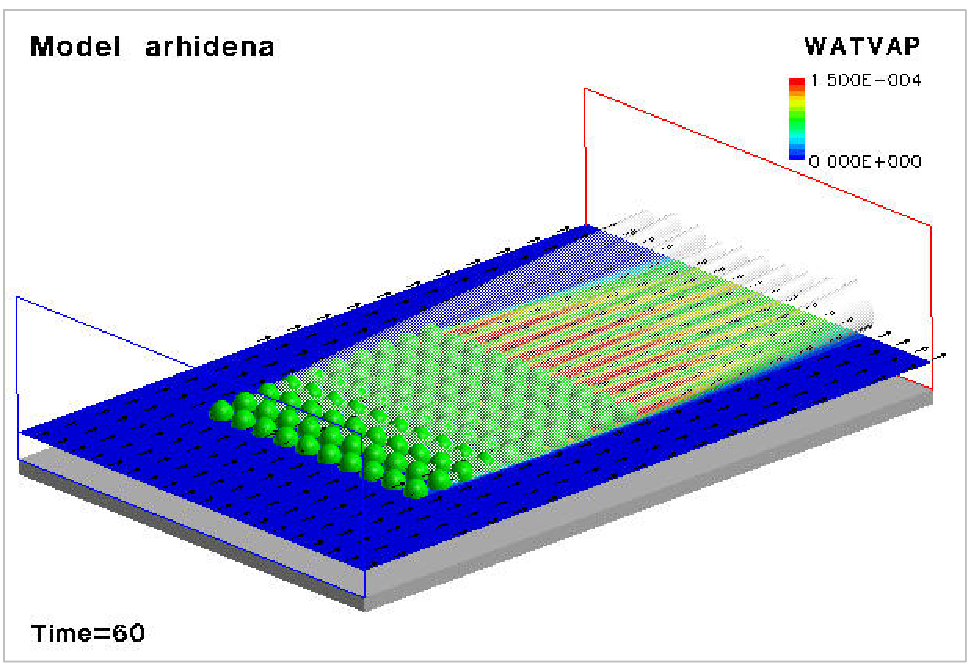
Model "arhidena" - Temperature Field Iso-View



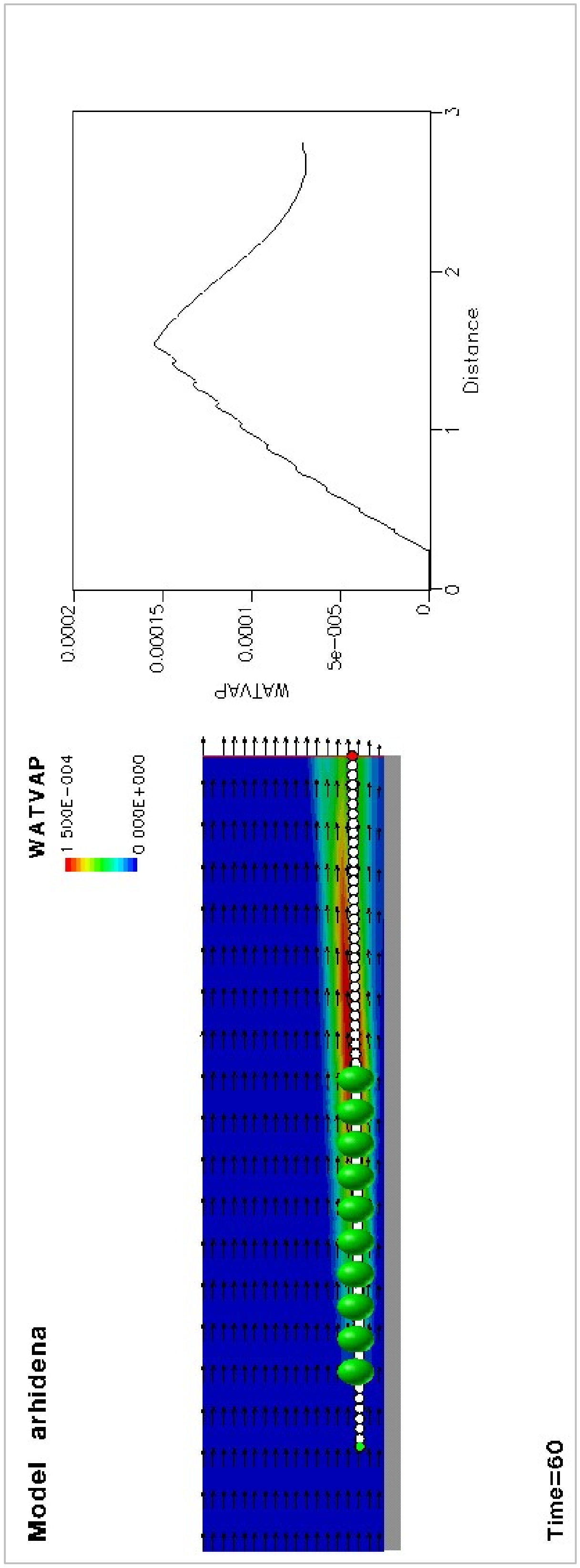
Model "arhidena" - Temperature Field Side View



Model "arhidena" - Water Vapor Field Iso-View

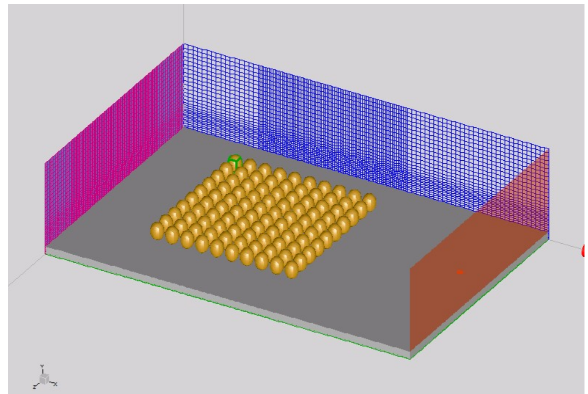


Model "*arhidena*" - Water Vapor Field Side View

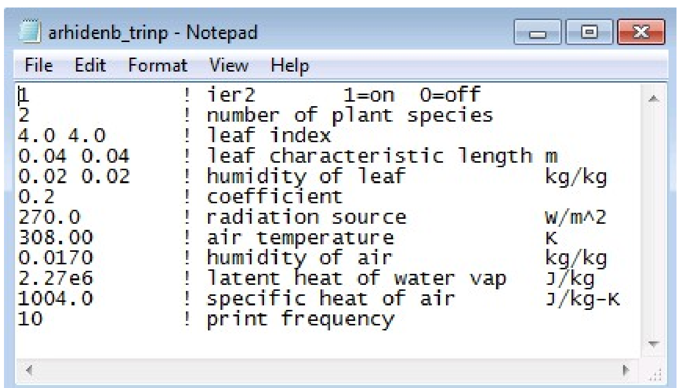


"High" DENSITY CFD Model Definition ("arhidenb")

Turbulent flow
Heat transfer activated
Mesh distribution: 96 I 32 J 68 K
1 inlet BC
1 outlet BC
100 porous media BCs
200 source BCs
Fluid I set to air (rho=1.177 kg/m^3)
Simulation timestep: 0.05 seconds
Tend: 60 second

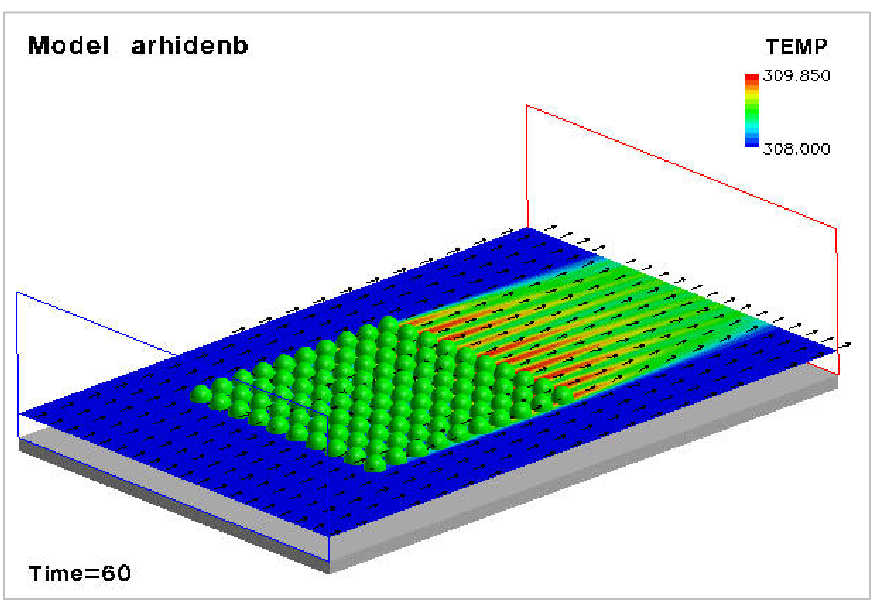


Model **"arhidenb"** *- Transpiration Input*

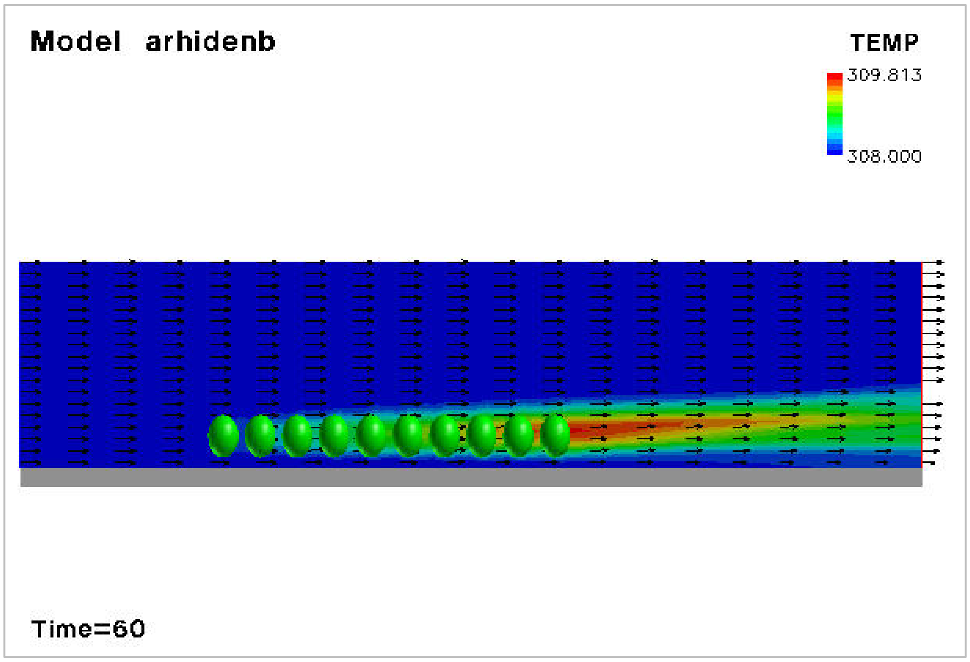


```
arhidenb_trinp - Notepad
File  Edit  Format  View  Help
1              ! ier2        1=on   0=off
2              ! number of plant species
4.0 4.0        ! leaf index
0.04 0.04      ! leaf characteristic length m
0.02 0.02      ! humidity of leaf            kg/kg
0.2            ! coefficient
270.0          ! radiation source            W/m^2
308.00         ! air temperature             K
0.0170         ! humidity of air             kg/kg
2.27e6         ! latent heat of water vap    J/kg
1004.0         ! specific heat of air        J/kg-K
10             ! print frequency
```

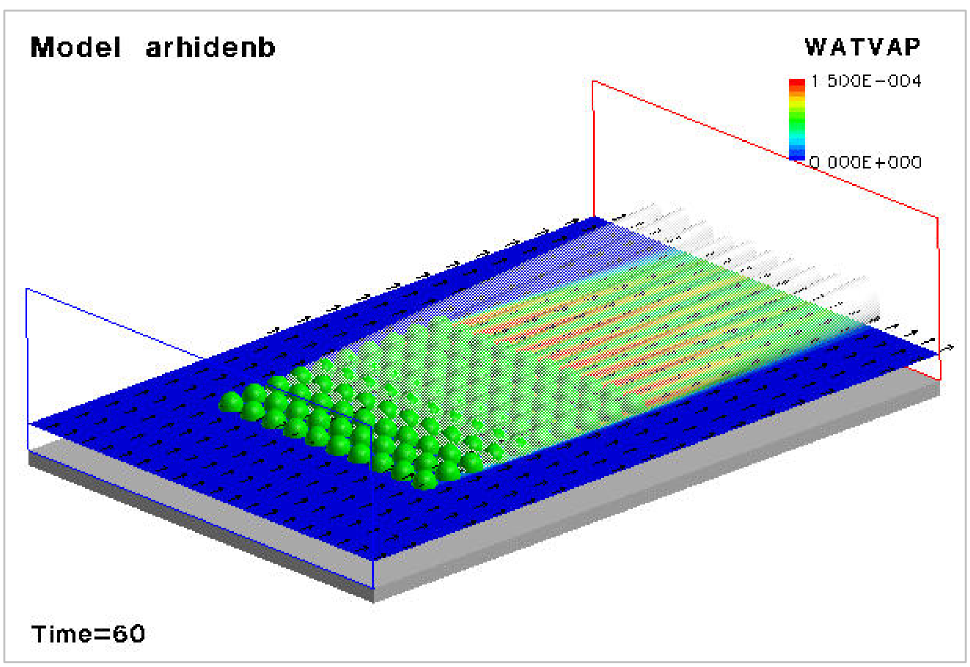
Model **"arhidenb"** *- Temperature Field Iso-View*



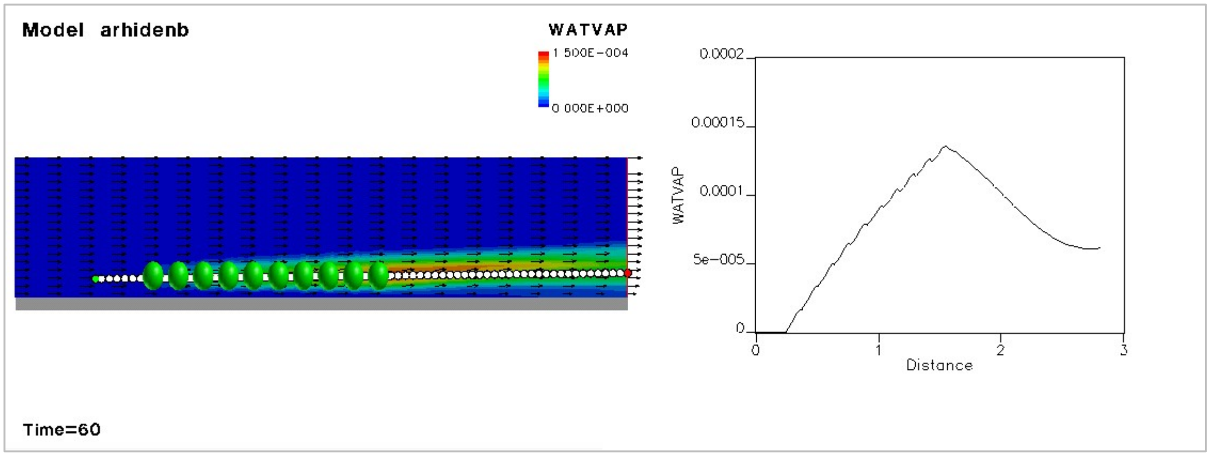
Model “arhidenb” - Temperature Field Side View



Model “arhidenb” - Water Vapor Field Iso-View



Model "arhidenb" - Water Vapor Field Side View

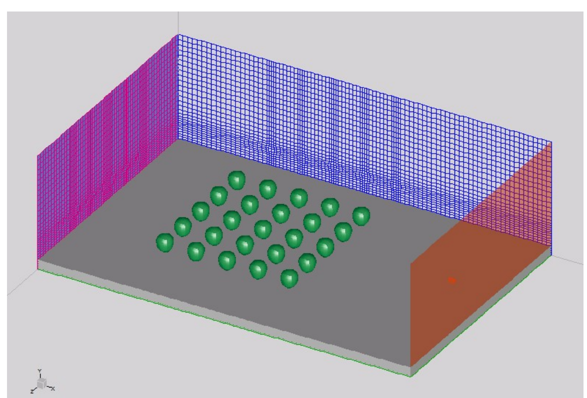


2.0.b Basil Simulations

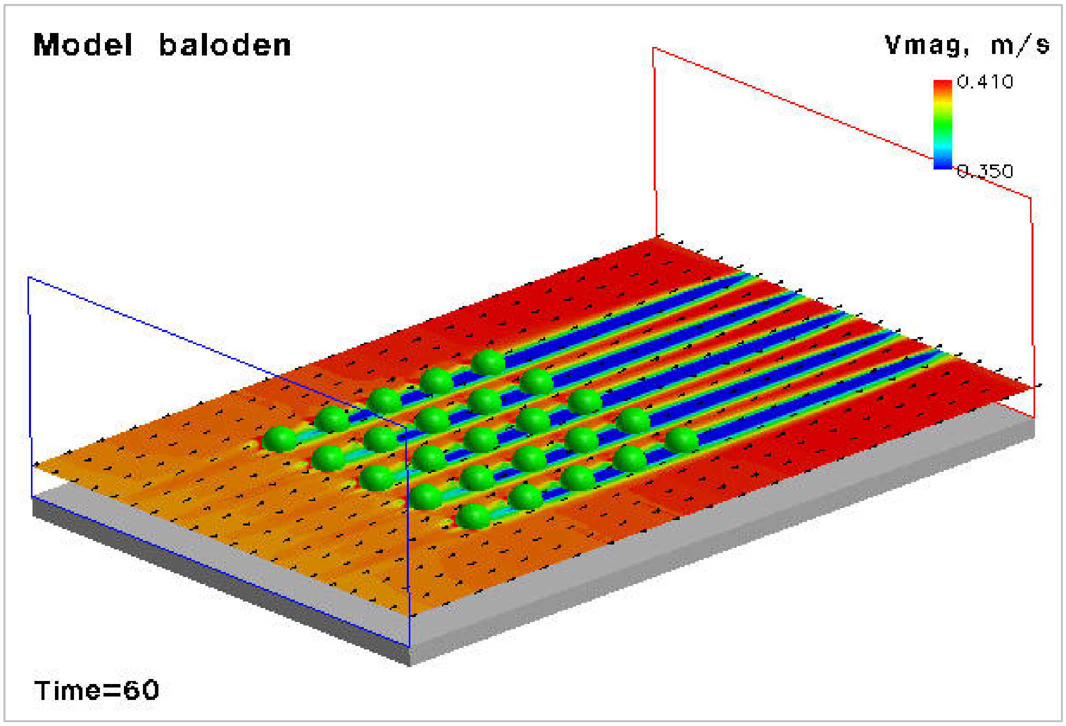
Two CFD models ares executed to generate the preliminary flow field solution restarts for both the "low" and "high" density plant scenarios. Subsequently, two (2) simulations are then executed for both scenarios varying temperature difference between plant leaf and air.

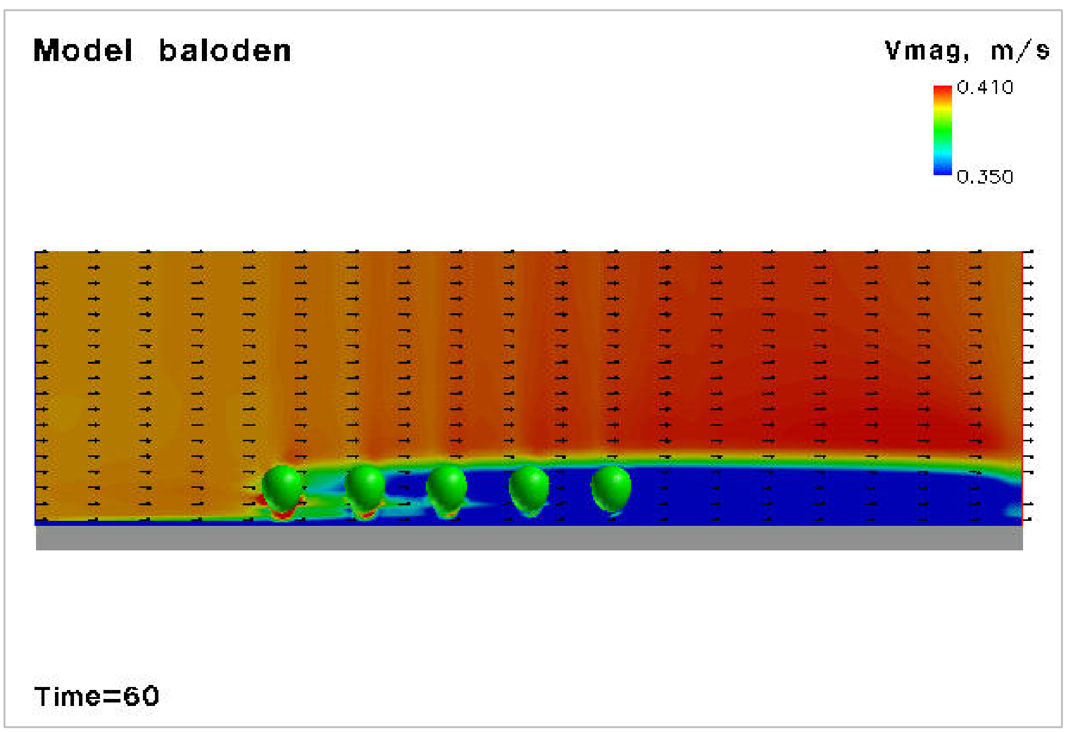
"Low" DENSITY CFD Model Definition ("baloden")

Turbulent flow
Heat transfer activated
Mesh distribution: 96 I 31 J 68 K
1 inlet BC
1 outlet BC
25 porous media BCs
Fluid I set to air (rho=1.177 kg/m^3)
Simulation timestep: 0.05 seconds
Tend: 60 second



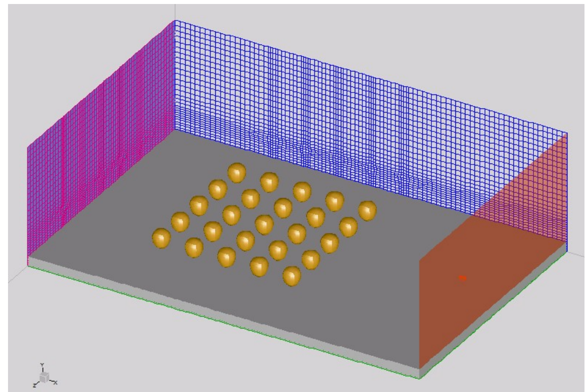
Model "baloden" - Velocity Magnitude





"Low" DENSITY CFD Model Definition ("balodena")

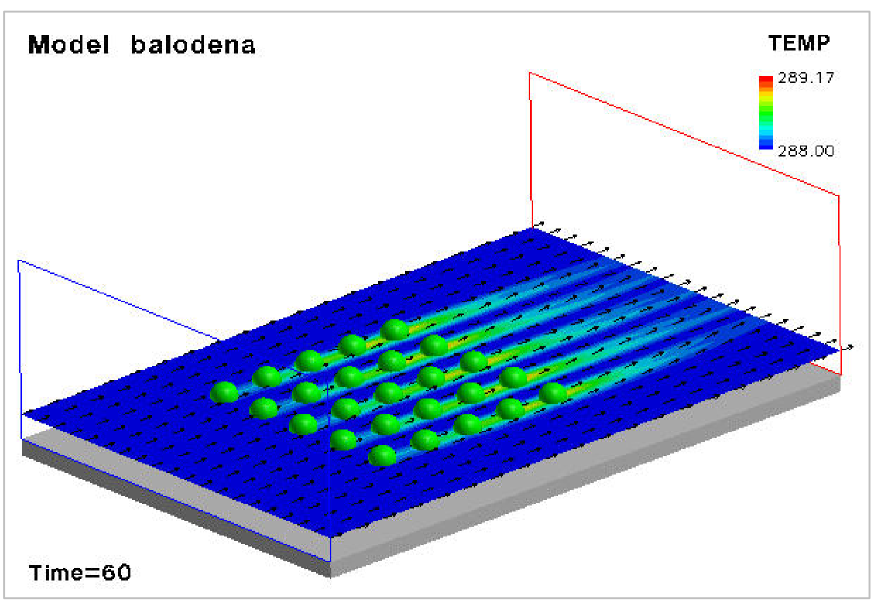
Turbulent flow
Heat transfer activated
Mesh distribution: 96 I 31 J 68 K
1 inlet BC
1 outlet BC
25 porous media BCs
50 source BCs
Fluid I set to air (rho=1.177 kg/m^3)
Simulation timestep: 0.05 seconds
Tend: 60 second



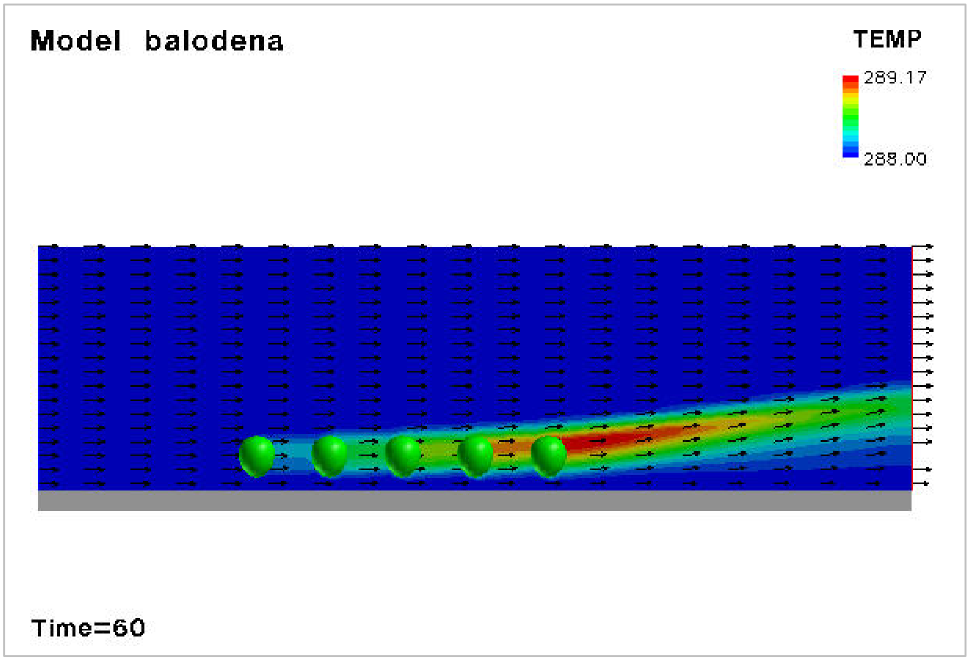
Model "balodena" - Transpiration Input

```
balodena_trip - Notepad
File  Edit  Format  View  Help
1               ! ier2       1=on  0=off
2               ! number of plant species
4.0 4.0         ! leaf index
0.04 0.04       ! leaf characteristic length m
0.02 0.02       ! humidity of leaf            kg/kg
0.2             ! coefficient
270.0           ! radiation source            W/m^2
288.00          ! air temperature             K
0.0190          ! humidity of air             kg/kg
2.27e6          ! latent heat of water vap    J/kg
1004.0          ! specific heat of air        J/kg-K
10              ! print frequency
```

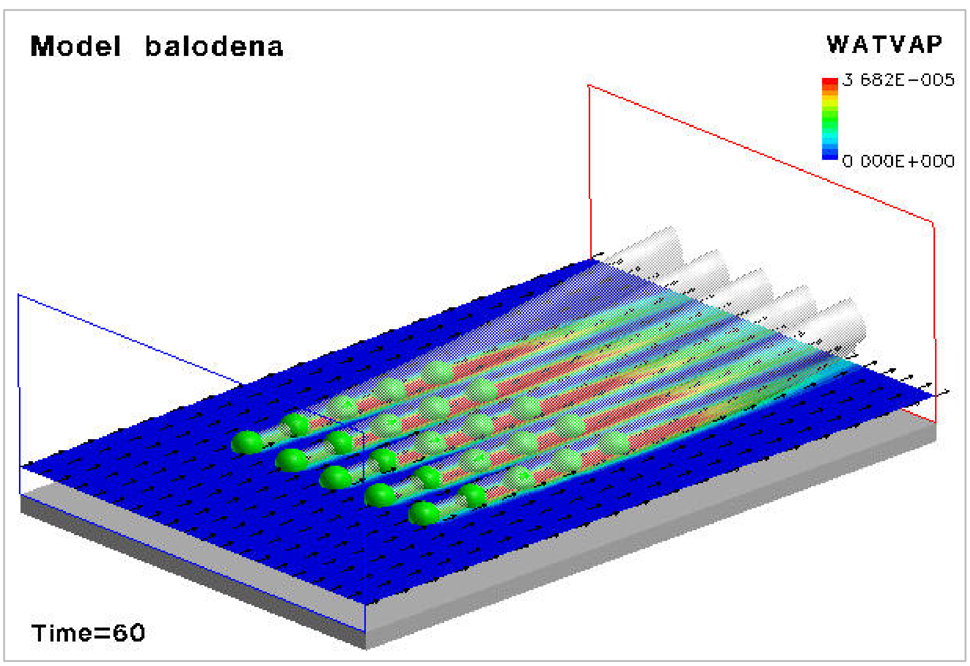
Model "balodena" - Temperature Field Iso-View



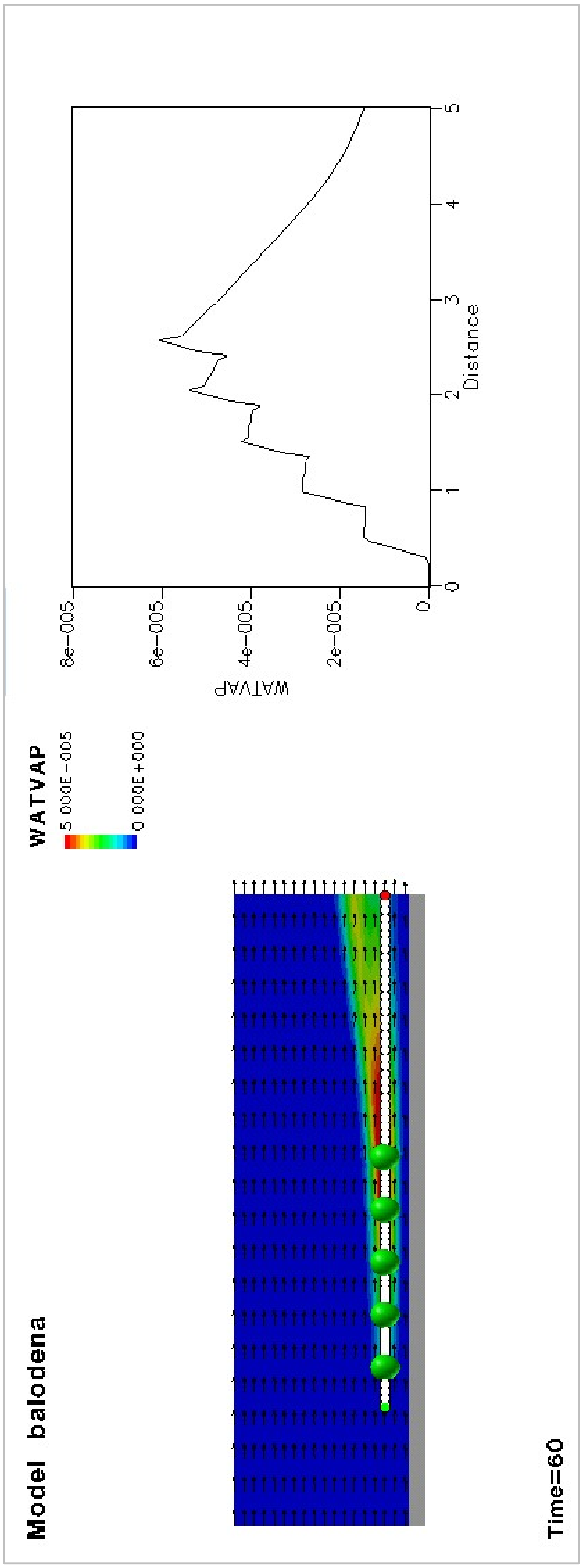
Model "*balodena*" - Temperature Field Side View



Model "*balodena*" - Water Vapor Field Iso-View

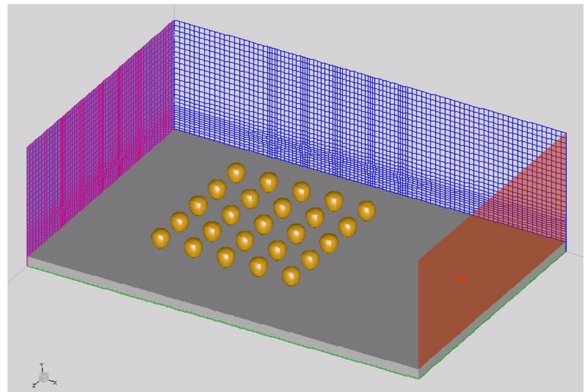


Model "**balodena*****" - Water Vapor Field Side View***

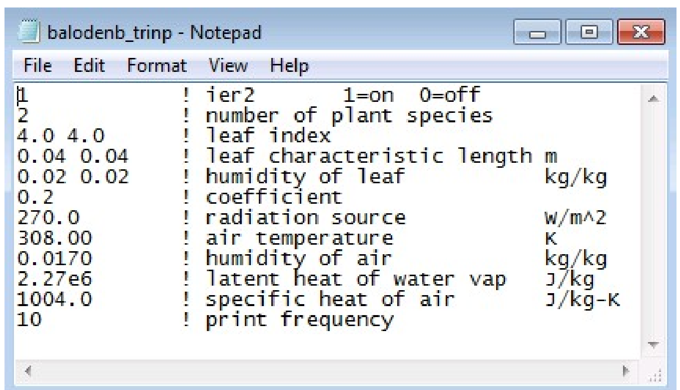


"Low" DENSITY CFD Model Definition ("*balodenb*")

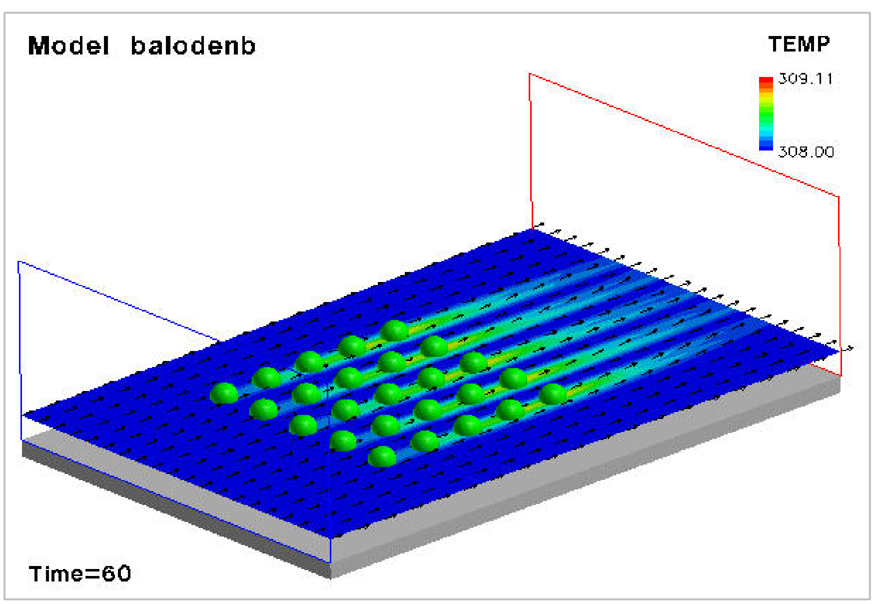
Turbulent flow
Heat transfer activated
Mesh distribution: 96 I 32 J 68 K
1 inlet BC
1 outlet BC
25 porous media BCs
50 source BCs
Fluid I set to air (rho=1.177 kg/m^3)
Simulation timestep: 0.05 seconds
Tend: 60 second



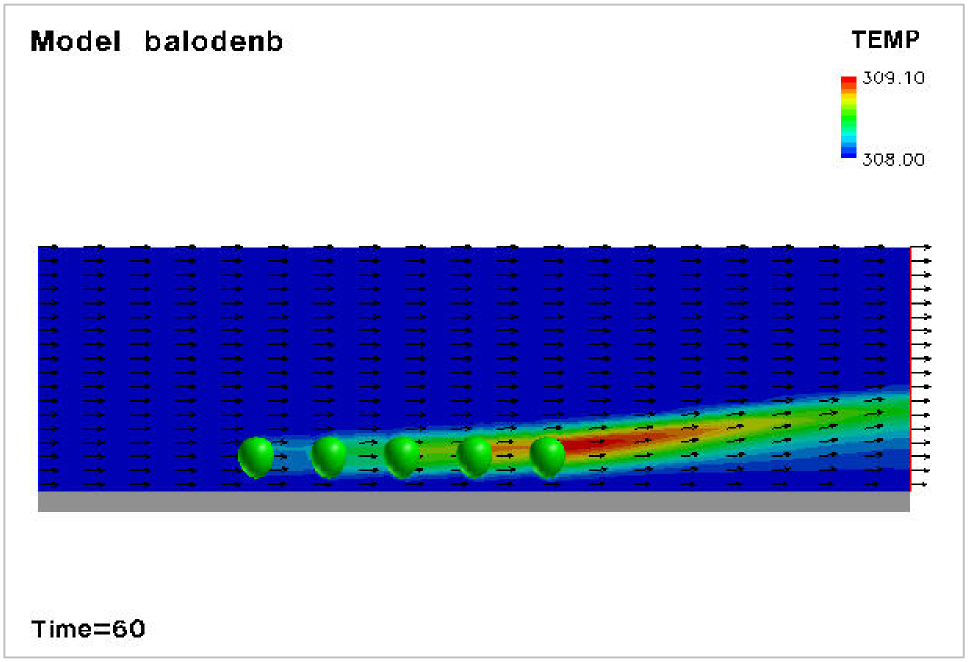
Model "*balodenb*" - Transpiration Input



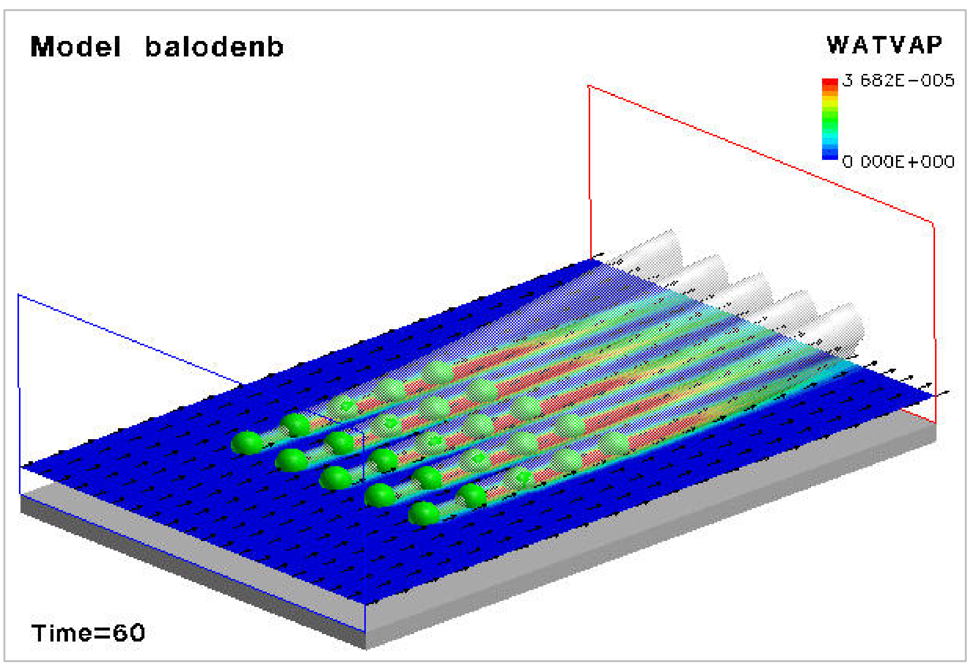
Model "*balodenb*" - Temperature Field Iso-View



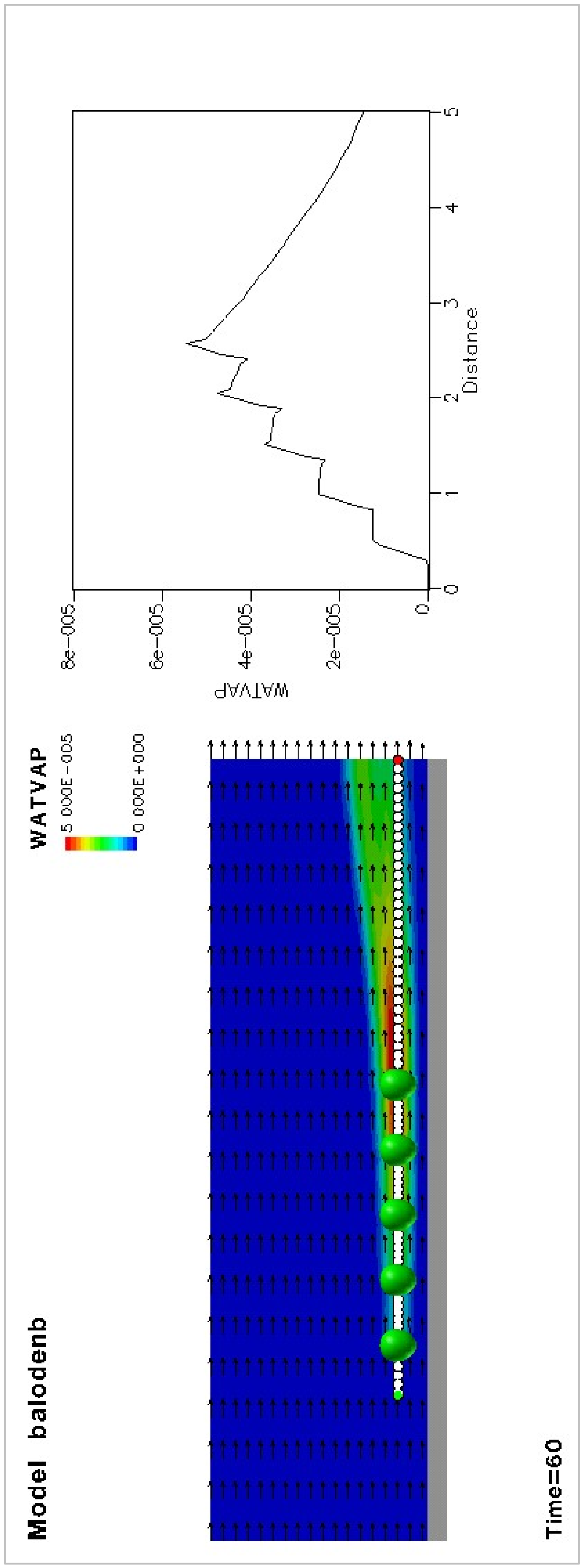
Model "**balodenb*****" - Temperature Field Side View***



Model "**balodenb*****" - Water Vapor Field Iso-View***

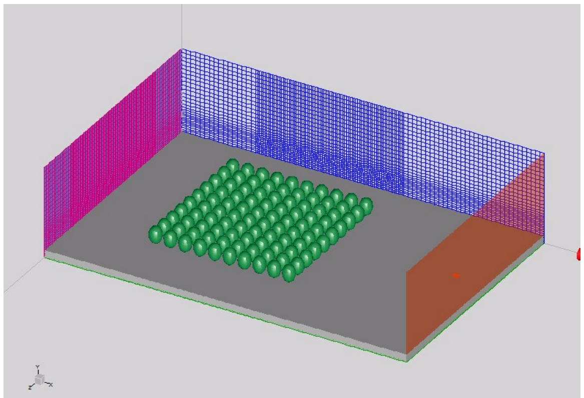


Model "*balodena*" - Water Vapor Field Side View

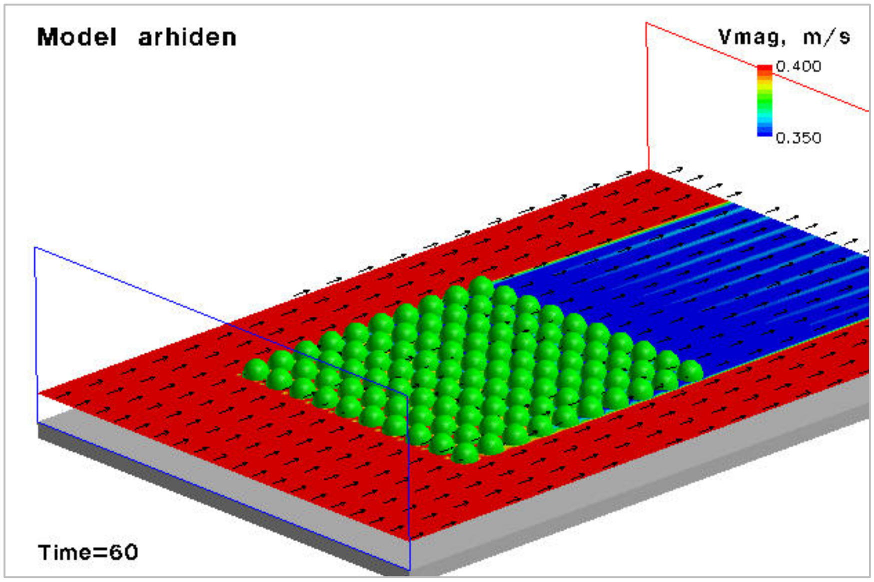


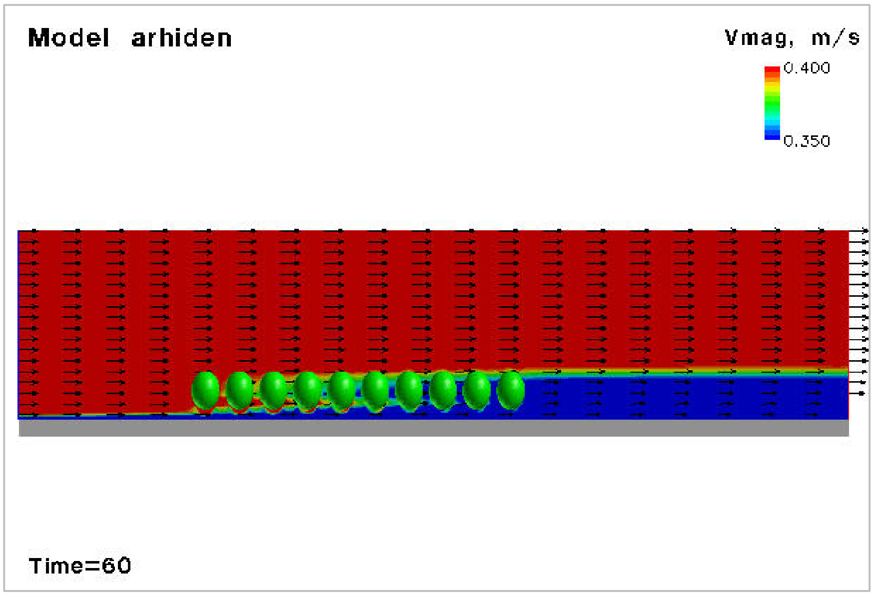
"High" DENSITY CFD Model Definition

Turbulent flow
Heat transfer activated
Mesh distribution: 128 I 32 J 106 K
1 inlet BC
1 outlet BC
100 porous media BCs
Fluid I set to air (rho=1.177 kg/m^3)
Simulation timestep: 0.05 seconds
Tend: 60 seconds (model "arloden")



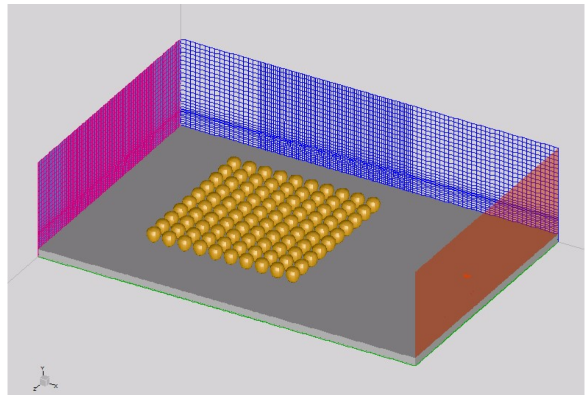
Model "**bahiden*****" - Velocity Magnitude***



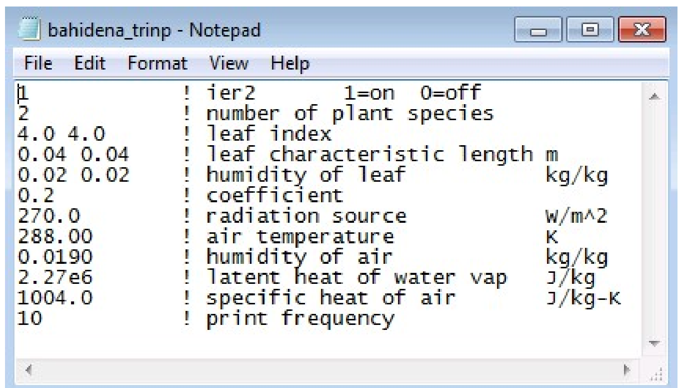


"High" DENSITY CFD Model Definition ("bahidena")

Turbulent flow
Heat transfer activated
Mesh distribution: 128 I 32 J 106 K
1 inlet BC
1 outlet BC
100 porous media BCs
200 source BCs
Fluid I set to air (rho=1.177 kg/m^3)
Simulation timestep: 0.05 seconds
Tend: 60 second



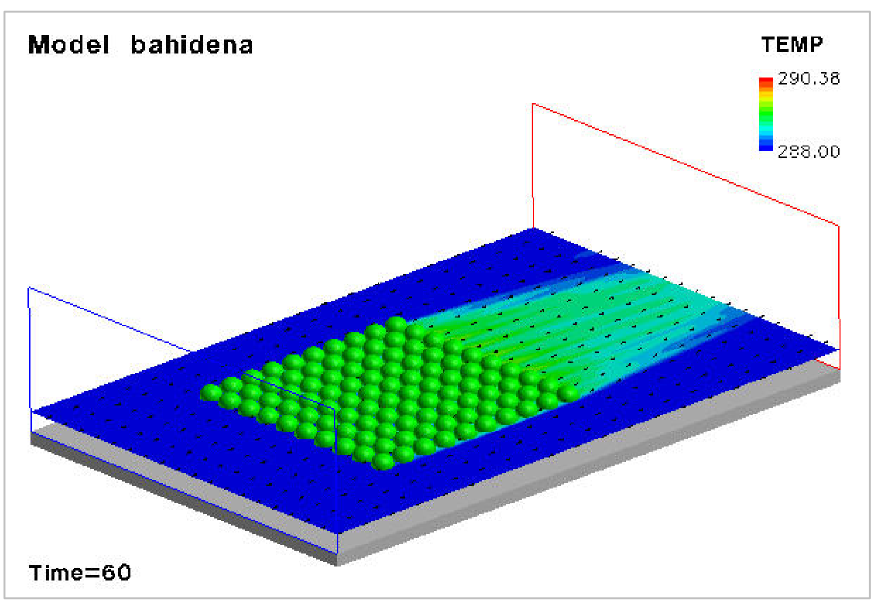
Model "bahidena" - Transpiration Input


bahidena_trinp - Notepad

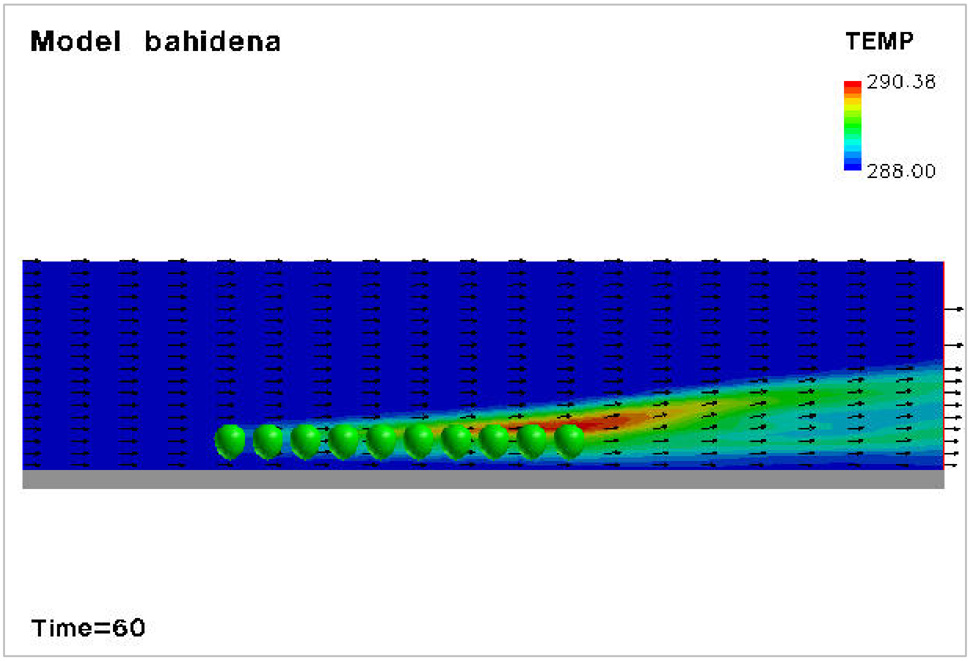
File Edit Format View Help

```
1              ! ier2        1=on   0=off
2              ! number of plant species
4.0 4.0        ! leaf index
0.04 0.04      ! leaf characteristic length m
0.02 0.02      ! humidity of leaf           kg/kg
0.2            ! coefficient
270.0          ! radiation source           W/m^2
288.00         ! air temperature            K
0.0190         ! humidity of air            kg/kg
2.27e6         ! latent heat of water vap   J/kg
1004.0         ! specific heat of air       J/kg-K
10             ! print frequency
```

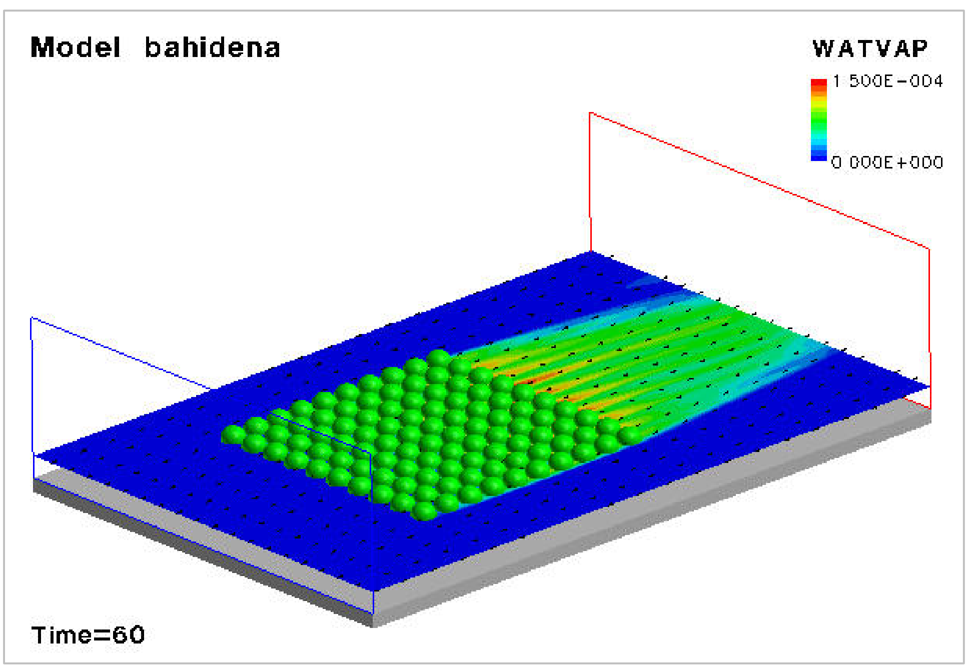
Model "bahidena" - Temperature Field Iso-View



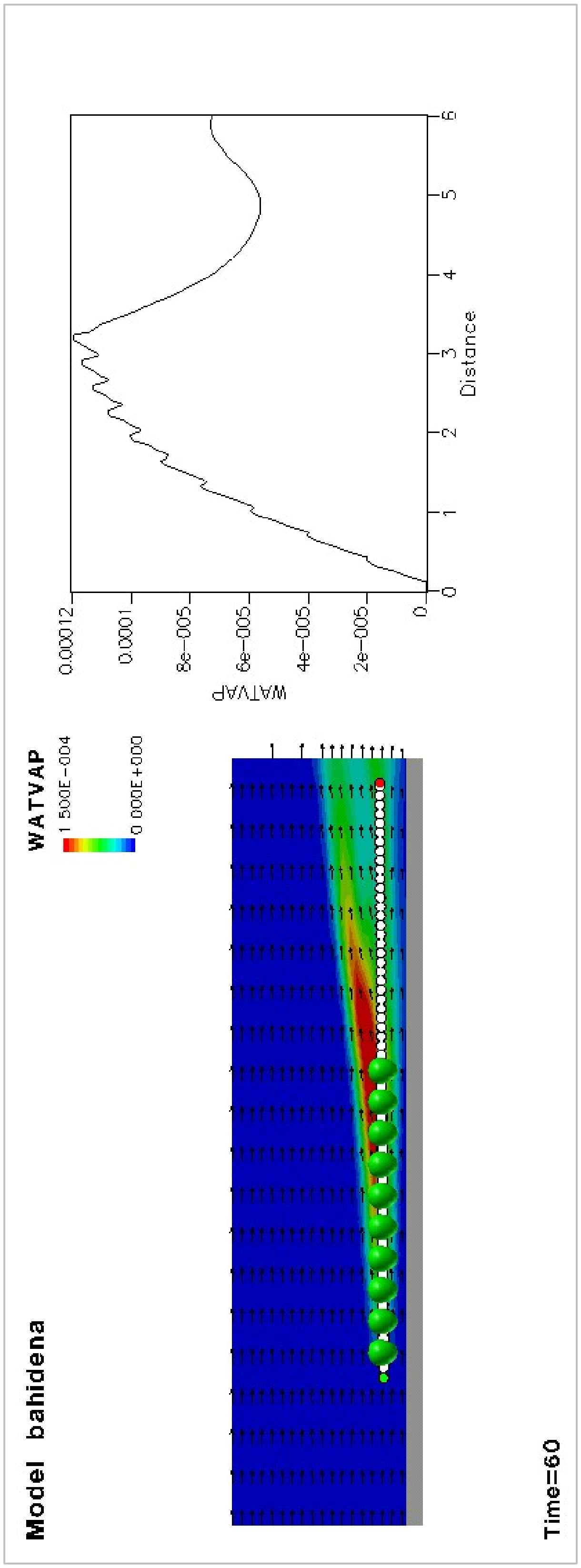
Model "**bahidena*****" - Temperature Field Side View***



Model "**bahidena*****" - Water Vapor Field Iso-View***

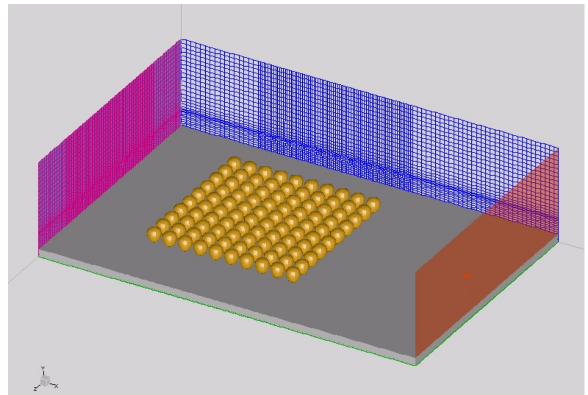


Model "**bahidena*****" - Water Vapor Field Side View***

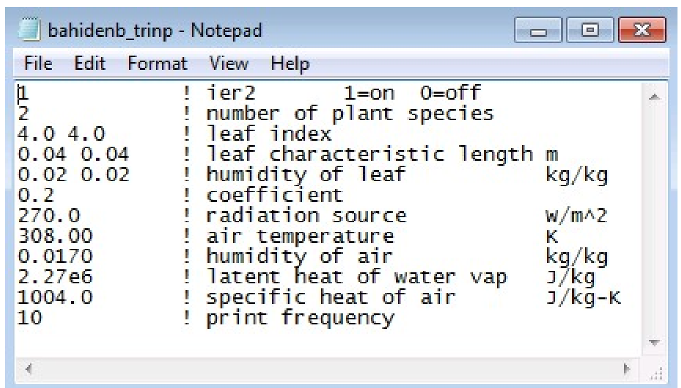


"High" DENSITY CFD Model Definition ("bahidenb")

Turbulent flow
Heat transfer activated
Mesh distribution: 96 I 32 J 68 K
1 inlet BC
1 outlet BC
100 porous media BCs
200 source BCs
Fluid I set to air (rho=1.177 kg/m^3)
Simulation timestep: 0.05 seconds
Tend: 60 second

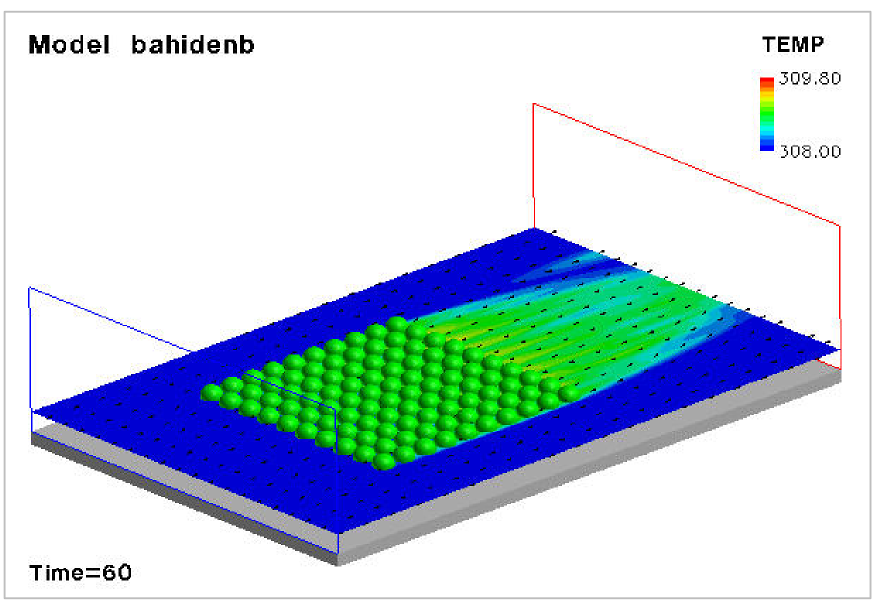


Model "bahidenb" - Transpiration Input

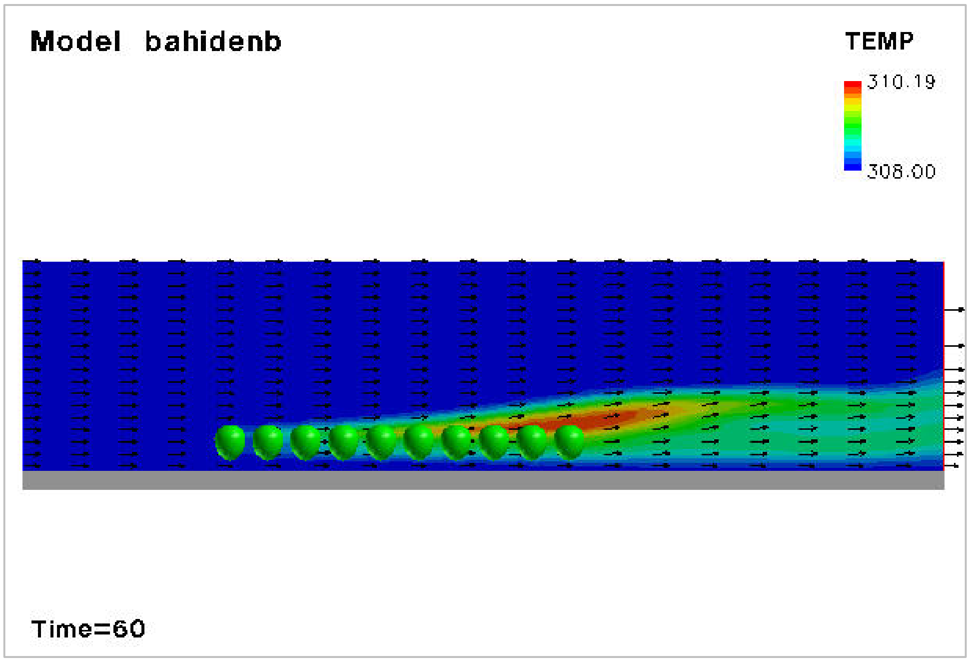



```
1               ! ier2        1=on  0=off
2               ! number of plant species
4.0 4.0         ! leaf index
0.04 0.04       ! leaf characteristic length m
0.02 0.02       ! humidity of leaf           kg/kg
0.2             ! coefficient
270.0           ! radiation source           W/m^2
308.00          ! air temperature            K
0.0170          ! humidity of air            kg/kg
2.27e6          ! latent heat of water vap   J/kg
1004.0          ! specific heat of air       J/kg-K
10              ! print frequency
```

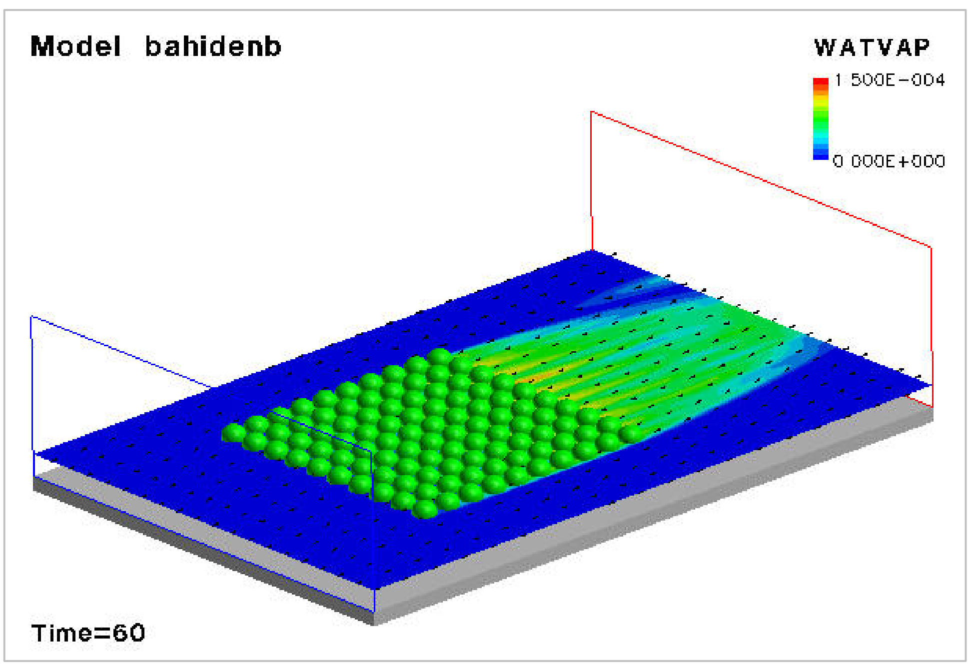
Model "bahidenb" - Temperature Field Iso-View



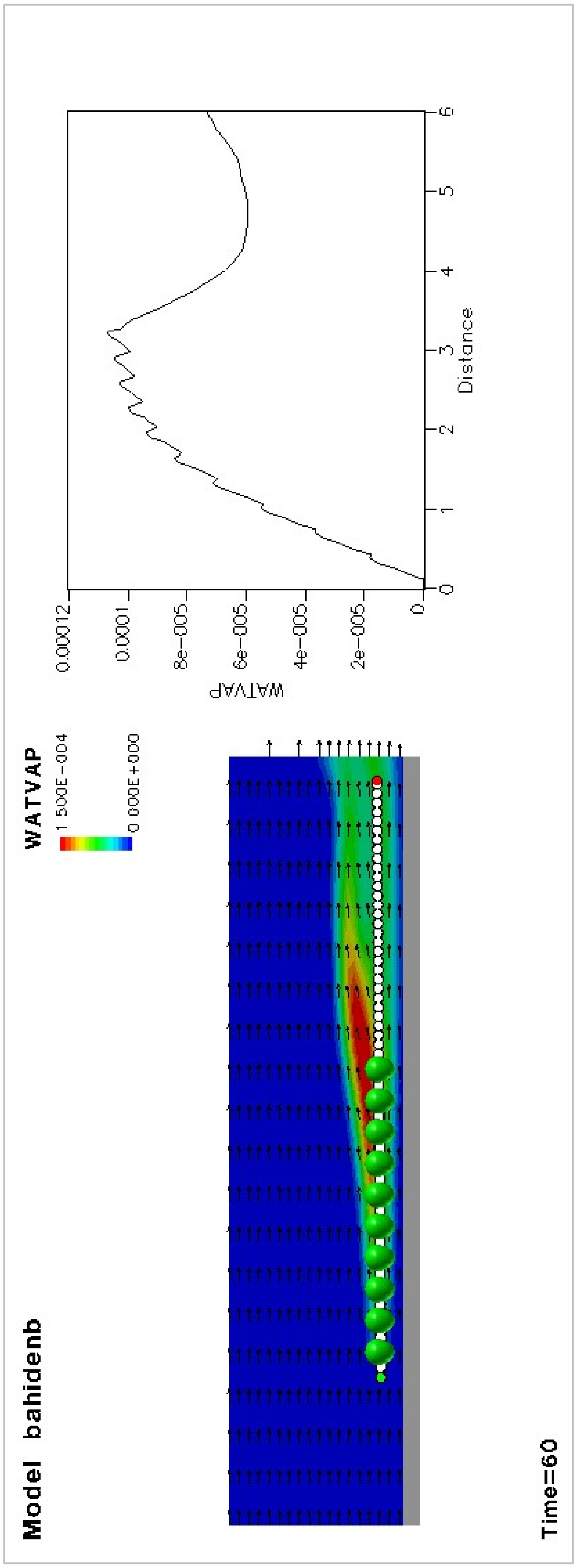
Model "bahidenb" - Temperature Field Side View



Model "bahidenb" - Water Vapor Field Iso-View



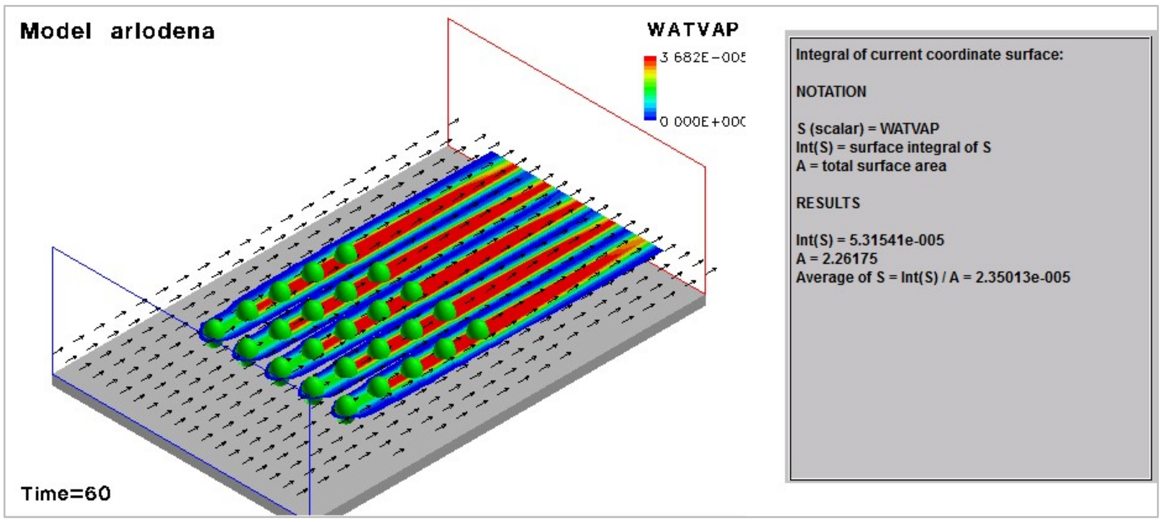
Model "**bahidenb*****" - Water Vapor Field Side View***



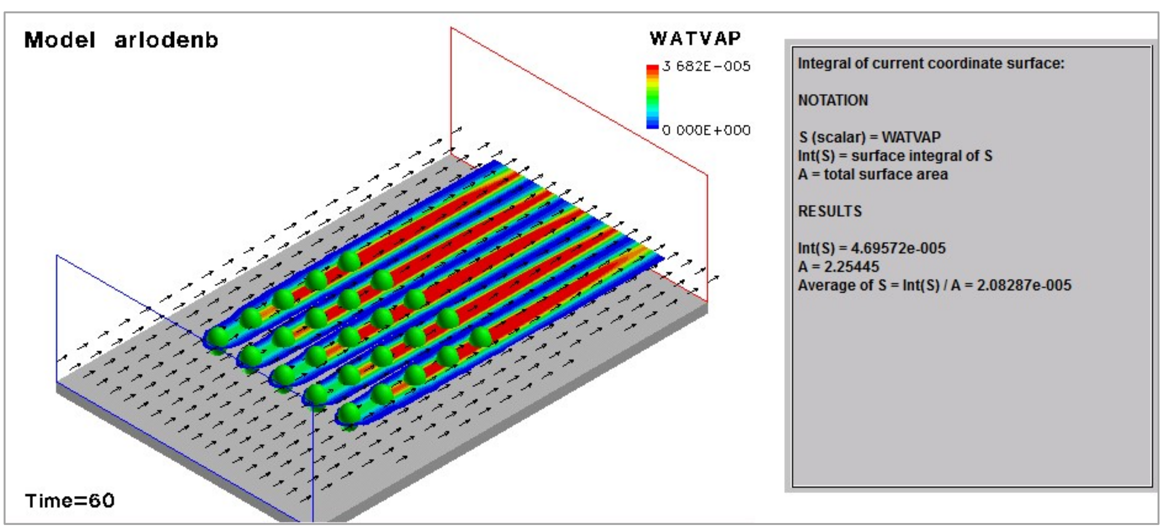
2.0.c Water Vapor Field Comparisons

The water vapor fields for the 8 CFD simulations presented in Section 3.0, are compared by integrating the WATVAP variable at the vertical centerline of the plant matrix (for values greater than 1e-7). The results are presented next.

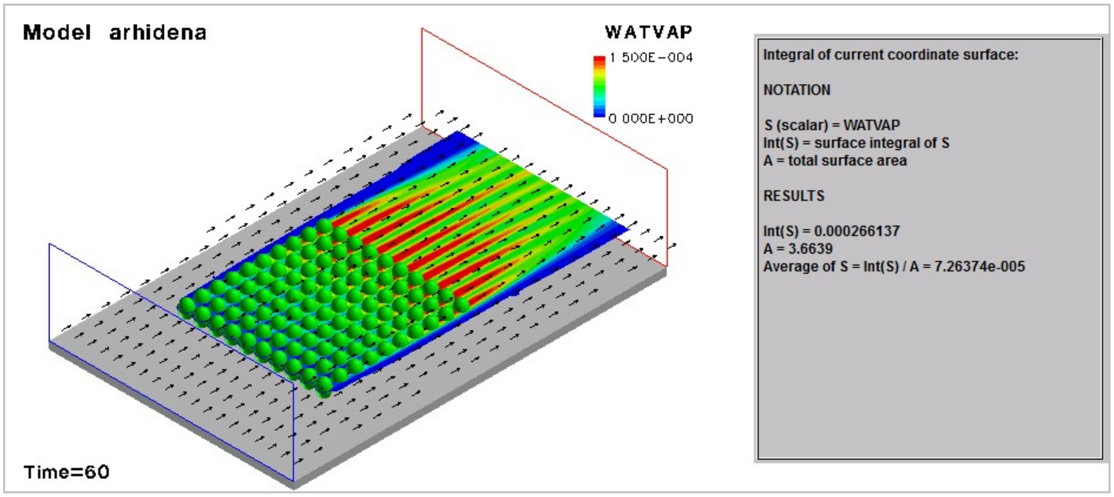
Arugula - Low Density / Low Temp



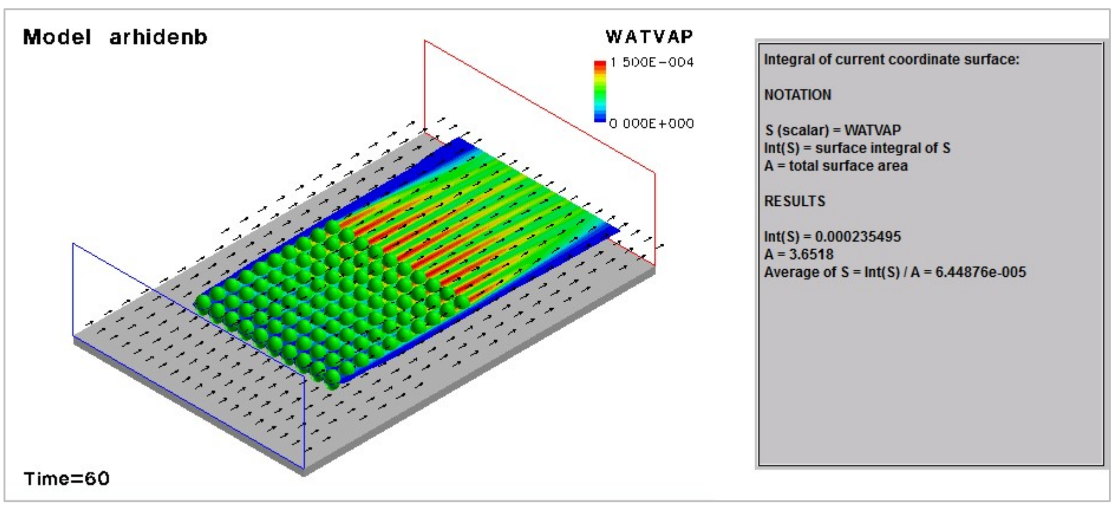
Arugula - Low Density / High Temp



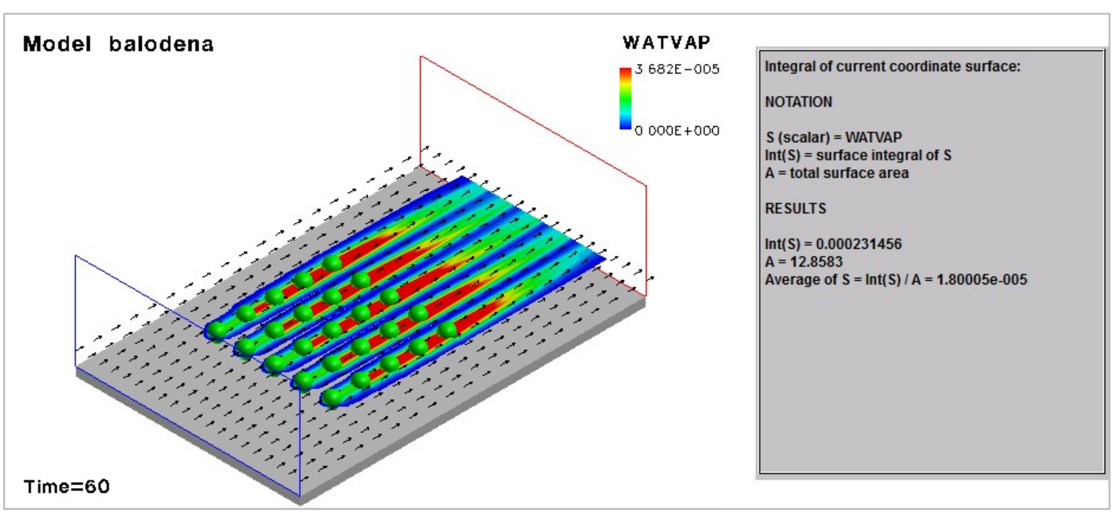
Arugula - High Density / Low Temp



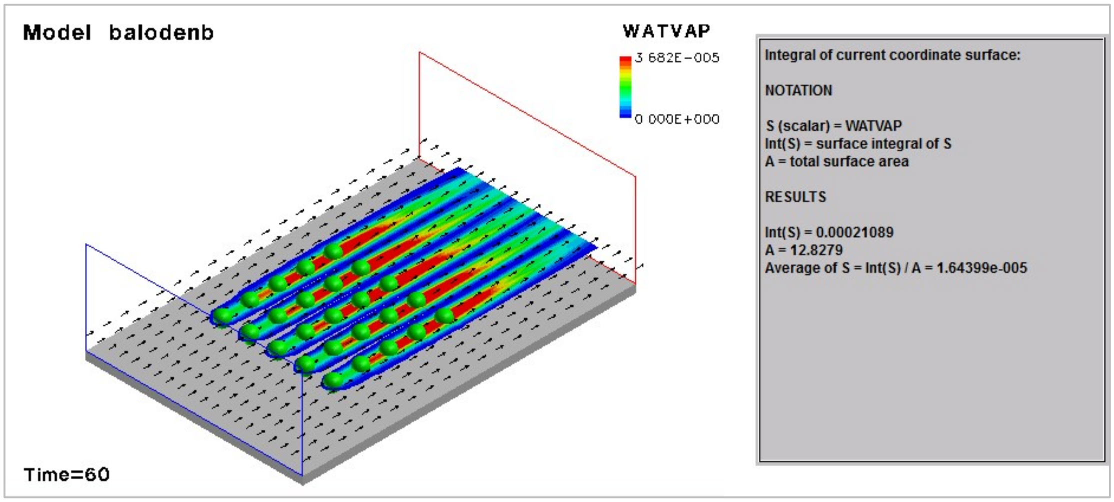
Arugula - High Density / High Temp



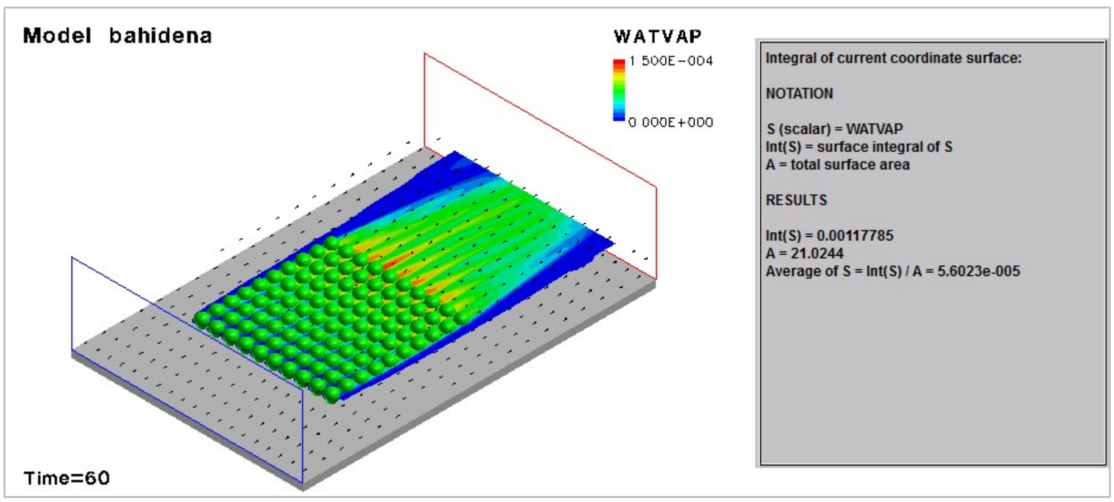
Basil - Low Density / Low Temp



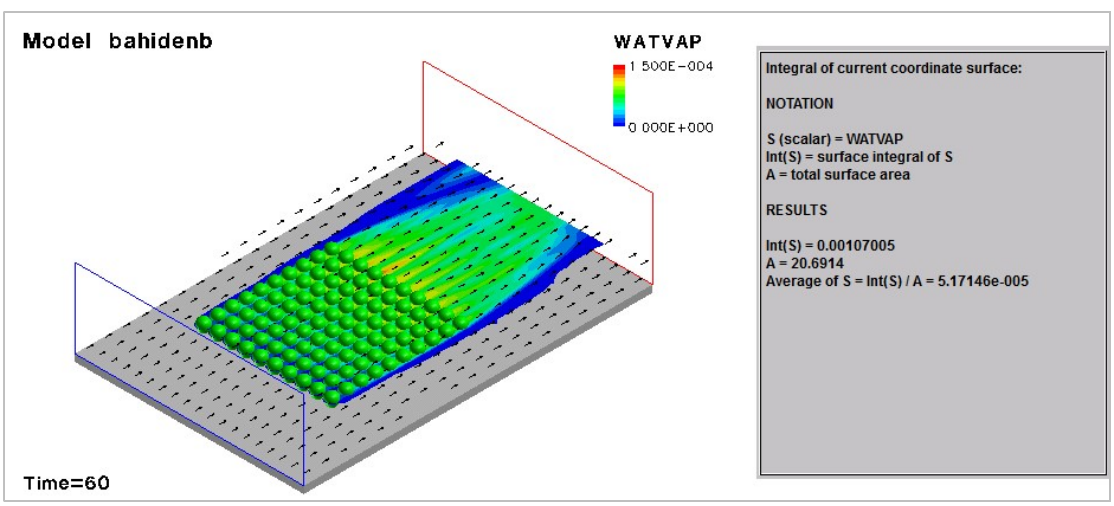
Basil - Low Density / High Temp



Basil - High Density / Low Temp



Basil - High Density / High Temp



The following table summarizes water vapor amount for the 8 CFD cases. The qualitative and quantitative analysis of the results show that the transpiration module is correctly simulating water vapor content based on various plant modeling scenarios.

RUN #	MODEL NAME	PLANT	AREA	WATVAP
1	arlodena	arugula	2.26	5.31e-5
2	arlodenb	arugula	2.25	4.69e-5
3	arhidena	arugula	3.66	2.66e-4
4	arhidenb	arugula	3.65	2.35e-4
5	balodena	basil	12.85	2.3e-4
6	balodenb	basil	12.83	2.1e-4
7	bahidena	basil	21.02	1.18e-3
8	bahidenb	basil	20.69	1.07e-3

Comparative Observations

1) All WATVAP amounts for "high" density plant configurations (Runs 1,2,5,6) contain ~4X the amount. This is expected as the number of plants between "low" and "high" plant density is 25:100 (or a factor of 4).

2) All "high" temperature cases result in a slightly lower WATVAP amount. This is consistent for both "low" and "high" density configurations

3) Basil simulations result in significantly higher WATVAP amounts. This is expected as the Basil plants are four times larger, resulting in approximately four times plant leaf surface area.

4) All eight simulations depict a rise in WATVAP content within the plant configuration array downstream from the specified inflow direction. This is expected, with the greatest rise observed in the "high" density configurations.

Note: The effect of higher humidity differences between plant leaves and air requires further research. The empirical relationships defining plant characteristics (e.g., leaf stomata and aerodynamic resistances) requires further review.

References

B. Morille, R. Genez, C. Migeon, P. Bournet, and H. Bouhoun Ali, CFD Simulations of the Distributed Climate Time-Evolution inside a Glasshouse at Night, UP EPHor Environmental Physics and Horticulture Research Unit, Angers France.

Majdoubi, Boulard et al, 2016, Canary Greenhouse CFD Nocturnal Climate Simulation, Journal of Fluid Dynamics, 6, 88-100.

Tae-Gyu Lim and Yong Hyeon Kim, 2014, Analysis of Airflow Pattern in Plant Factory with Different Inlet and Outlet Locations using Computational Fluid Dynamics", Journal of Biosystems Engineering, 39(4):310-317.