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The Effect of Internal Obstructions in Naturally Ventilated Greenhouse Applications

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ABSTRACT

In this paper the effect of internal partitions on airflow and temperature patterns in a glass greenhouse is presented. The inner climate at plant level of the greenhouse is numerically analysed using computational fluid dynamics. Firstly, the results obtained for an open greenhouse were validated against results found in the literature. Next a full length partition was inserted in the middle of the two west-spans of the greenhouse. The second case investigated the influence of a partition half the height of the full partition. Results showed that the presence of a full partition has a significant influence on both velocity and temperature distribution at plant level. Reducing the height of the partition results in a less pronounced influence on the temperature and velocity distribution compared to the full partition.

INTRODUCTION

Greenhouses generally provide a protective environment for plants in order to typically produce horticultural crops out-of-season. Ventilation of greenhouses is vital to control air temperature, to renew carbon dioxide supply and to reduce the relative humidity of the greenhouse. If the temperature in the greenhouse becomes too high, the internal structure of the plants can start to disintegrate. If insufficient carbon dioxide is available, plant growth is restricted as this is required for photosynthesis. Certain fungus spores germinate only when the relative humidity is too high. Therefore ventilation aids in preventing plant disease. [1]

Different types of ventilation systems exist for ventilating greenhouses, but since the recent emphasis on energy conservation, the popularity of natural ventilation methods is increasing. Built-in vents in the greenhouse construction are opened to allow hot air to rise and escape through these vents.

Various configurations of vents can assist in controlling the greenhouse temperature and indoor environment. Natural ventilation depends on a number of factors such as wind characteristics, air temperature differences between the inside and outside, greenhouse design and the presence of plants [2]. Since the greenhouse climate depends on all the mentioned parameters, the prediction of air flux exchanges and mixing is highly uncertain. Some aspects still require intensive research, for example the strategy to accurately design natural ventilation for maintaining sufficient circulation and good heat and mass transfer between plants and air.

Computational Fluid Dynamics is a useful tool for investigating the flow in and around a greenhouse structure. Recent advances in this field have increased the popularity of this method, and have been used in several studies to investigate the natural ventilation of various types of greenhouses [2],[3],[4]. Bartzanas et al investigated the effect of vent arrangement on windward ventilation of a tunnel greenhouse [3]. A numerical model was constructed and validated against experimental data collected in an identical greenhouse. The CFD model was modified to investigate the influence of four different vent arrangements on the natural ventilation.

The results indicated that for evaluating the performance of various ventilation systems, the best criterion is not necessarily the highest obtainable ventilation rate. Other criteria that should be taken into consideration as well are air velocities and corresponding aerodynamic resistance in the region covered by the crop and air temperature differences between the inside and outside of the greenhouse. These criteria led to the conclusion that a combination of roof and side openings provides an appropriate solution for ventilation [3].

In a study done by Ould Khaoua et al [2], the ventilation efficiency of a greenhouse was analyzed by utilising CFD. The influence of wind speed and roof vent configuration on airflow and temperature patterns in a compartmentalised greenhouse was investigated. They found that the ventilation rate efficiency was considerably increased by orientating the roof vents windward.

Another study was conducted by Bartzanas et [4] al where they analyzed the ventilation in a naturally ventilated tunnel greenhouse equipped with insect-proof screens. Their conclusion was that insect-proof screens and wind direction had a significant effect on the greenhouse climate.

The objective of the current investigation is to numerically model the influence of partitions on the climate inside a greenhouse similar to the greenhouses discussed previously.

COMPUTATIONAL FLUID DYNAMICS

Governing Equations

In Computational Fluid Dynamics a numerical solution of partial differential equations, typically the Navier-Stokes Equations, are obtained [5]. These equations govern the transport of mass, momentum and energy in moving fluids. [6] Three laws govern the transport of the above quantities: conservation of mass, Newton's second law of motion and the first law of thermodynamics [6]. Finite volume discretization is the first step in solving these transport equations. This method subdivides the solution domain into a finite number of small control volumes, which corresponds to the cells of a computational grid. Discrete versions of the integral form of the continuum transport equations are applied to each volume. The objective of this method is to obtain a set of linear algebraic equations. An algebraic multigrid solver is then used to solve the resulting linear equations. [7]. To illustrate this, the transport of a simple scalar will be considered. The continuous Integral form of the governing equation is typically given by [7]:

$$\frac{d}{dt}\int_V \rho\phi dV + \oint_A \rho\phi\left(v - v_g\right)\cdot da = \oint_A \Gamma\phi \cdot da + \int_V S_\phi dV \quad (1)$$

Where $\rho =$ density
$\phi =$ scalar quantity
V = cell volume
$\bar{v} =$ velocity
$\bar{v}_g =$ grid velocity
$\Gamma =$ diffusion coefficient
$\bar{a} =$ coefficient arising from Finite Volume Discretization
$S_\phi =$ Source Term

The first term is the transient term, which is generally only included in transient calculations. The second term is the convective flux, third term the diffusive flux, and lastly the volumetric source term. The mathematical formulation of each term is also defined in the StarCCM+ documentation [7]. If Equation 1 is discretized, the following equation results:

$$\frac{d}{dt}(\rho\phi V)_0 + \sum_f \left[\rho\phi(\bar{v}\cdot\bar{a} - G)\right]_f = \sum_f (\Gamma\nabla\phi\cdot\bar{a})_f + (S_\phi V)_0 \quad (2)$$

Where G = grid flux computed from mesh motion

A detailed description of a discretization procedure can be found in Patankar [8] In order to include buoyancy source terms in the momentum equation, the gravity model was activated. To approximate the buoyancy source term, the Boussinesq model is implemented by selecting a constant density flow. The Boussinesq model is shown below:

$$f_g = \rho\bar{g}\beta\left(T_{ref} - T\right) \quad (3)$$

Where $\bar{g}$ = gravitational vector
$\beta =$ Coefficient of Bulk Expansion
$T_{ref} =$ Operating Temperature.

To solve the conservation equations for mass and momentum simultaneously, the coupled flow model was chosen, which solves the momentum and energy equations using a time or pseudo time marching approach. [7]. Previous investigations have indicated the turbulent nature of both the inner and outer flow in greenhouses [9]. In StarCCM+ turbulence is also simulated by solving the Reynolds-averaged governing equations for momentum, energy and scalar transport. Various turbulence models are available in StarCCM+, for this investigation the standard *k*-ε model was implemented. This model is a two-equation model in which transport equations are solved for the turbulent kinetic energy *k* and its dissipation rate ε. The transport equations used are in the form suggested by Jones and Lander [10]. Additional terms have been added in StarCCM+ to account for buoyancy (in this case the Boussinesq approximation) and compressibility effects.

The effects of the small ornamental plants grown inside the greenhouse were taken into consideration in the current as well as previous simulations. Simulations on the current greenhouse were done using the StarCCM+ solver [7]

Numerical Model

The CFD model in this paper is based on a greenhouse used in a study by Ould Khaoua [2] It is a glass fourspan greenhouse (width, 4 by 9.60m;length, 68m; eaves height, 3.90m; ridge height, 5.9m). The greenhouse (Figure 1) is covered by 4mm thick horticulture glass and has continuous roof vents on both sides of each span. During the experimental period, ornamental 0.2m high plants were grown on 0.75m shelves. The length of the shelves were assumed, and the ventilator openings were assumed to be 1.22m wide [1]. The negative y direction was chosen as the direction of the gravitational constant. The wind was modelled to act in an eastern direction.

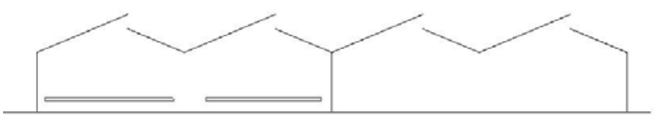

Figure 1: *Model of the Fourspan Greenhouse with ventilators opened to the leeward side.*

Grid Refinement and Boundary Conditions

In order to avoid interference with the internal flow, a large control volume was created around the greenhouse, with the outflow section defined far downstream. The total length of the control volume was 334m, while the height measured 160m. The entire solution domain was meshed using a polyhedral meshing model. The main advantage of using polyhedral cells instead of tetrahedral cells is that a polyhedral mesh contains approximately 5 times fewer cells than an equivalent tetrahedral mesh for a given surface [7]. This meshing model utilizes an arbitrary polyhedral cell shape to assemble the core mesh. A special dualization scheme is used to create the polyhedral mesh based on an underlying tetrahedral mesh automatically created in the process. Table 1 summarizes the boundary conditions used in the simulations, while Table 2 Summarizes the properties used in the turbulence model.

Table 1: *Boundary Conditions for CFD Mode [2]*

PARAMETERS	VALUES
Inlet Air	
Velocity at 6m [m/s]	**1.4**
Temperature [°C]	**22.2**
Temperature [°C]	
Outside Air	22.2
Outside Ground	27.9
Inside Ground	27.3
Roof	33.6
Plastic Central Partition	31.3
Glass Walls	29.1

Table 2: *K-Epsilon Turbulence Model Parameters used*

Under Relaxation Factor	0.8
Convergence Tolerance	0.1
Epsilon	0.0
Turbulent Viscosity (Under Relaxation Factor)	1.0

The mesh in the region around and inside the greenhouse was refined using a volume shape with a relative size to the base mesh size (Figure 2). After careful consideration and initial poor results, it was decided to create a refined mesh with a relative size of 5%. In order to adequately model the turbulence, the prism layer meshing model [7] was also incorporated. The prism layer mesh consisted of five orthogonal prismatic cells right next to the boundaries in the volume mesh. The mesh was converted to a two-dimensional mesh after the volume mesh was created. The final mesh consisted of 30 238 polyhedral cells.

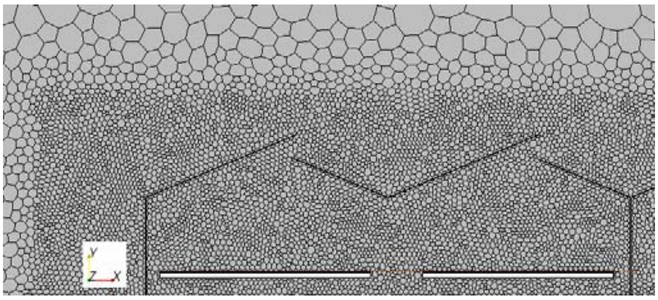

Figure 2: *Refined mesh around Greenhouse*

For initial simulation purposes the top part of the control volume was specified to be a symmetry plane, while the outlet was defined as a flow-split outlet. Initial simulations with a steady state approach resulted in poor convergence. Therefore as an initial solution, a steady flow was assumed, after which an implicit unsteady solver was activated. StarCCM+ employs the SIMPLE algorithm to control the overall solution. More details on this algorithm can be found in the StarCCM+ Manuals [7] and Patankar [8].

RESULTS

In order to validate the CFD model of the current greenhouse, the results have been compared to the results obtained by Ould Khaoua et al [2]. The wind was assumed to enter perpendicularly to the greenhouse from the left, with a uniform velocity of 1m/s. [3]. Two cases were considered next, the first case having a partition wall placed in the centre of the two west spans, while the second case incorporated a partition only half the height of the previous partition wall.

Figure 3 shows a scalar plot of the temperature distribution through the west span of the greenhouse (Figure 3), as well as a scalar plot of the velocity magnitude inside the west span. The flow of interest is contained in the first two compartments of the greenhouse (West Spans), where a temperature of approximately 301K was observed in the vicinity of the left corner of the roof.

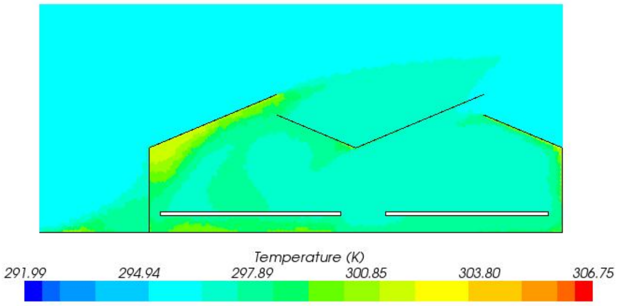

Figure 3: *Temperature Distribution inside two West Spans of Greenhouse*

The temperature inside the first two spans of the greenhouse is on average 2°C higher than the temperature of the incoming air. The temperature increases slightly towards the front half of the west span.

The velocity distribution inside the west span of the compartment is relatively low compared to the outside wind velocity (Figure 4). Air is sucked in through the second roof vent, and splits into two separate streams in the middle of the greenhouse. Part of the air stream moves towards and out the first roof vent, while some of the flow created a clockwise rotating cell in the first half of the west span. In the second half a counter clockwise rotating cell is formed, with some of the flow moving underneath the shelves with a lower magnitude in the first half, but slightly higher in the right half. The same phenomenon was observed in the greenhouse analyzed in the literature [2]

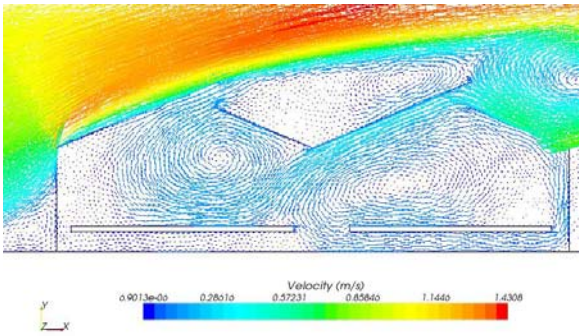

Figure 4: *Velocity Vectors inside West Span of Greenhouse*

Figure 5 illustrates the normalized velocities found in the literature for this greenhouse (similar to the greenhouse in the literature [2]), while Figure 6 shows the velocities obtained with the current simulation using StarCCM+ CFD model. The velocities were obtained at plant level (1m height).

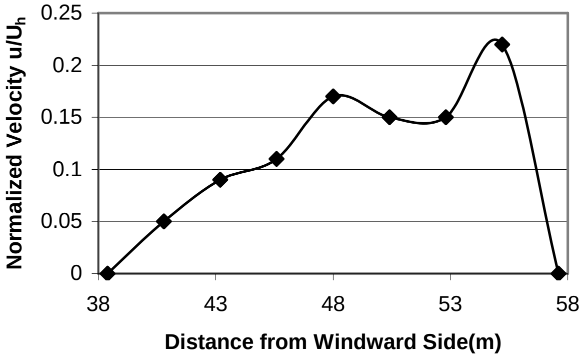

Figure 5: *Normalized Velocity for Greenhouse in Literature*

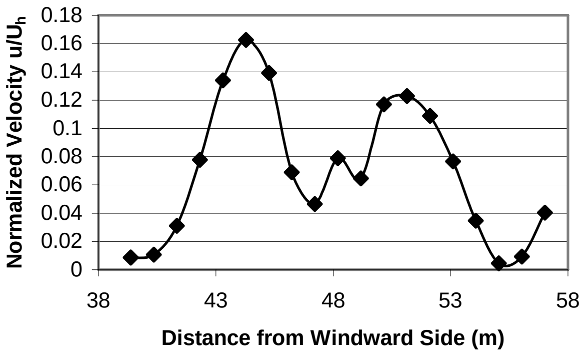

Figure 6: *Normalized Velocity obtained for the current CFD model.*

From the above graphs it can be seen that there is some air movement present. Comparing the two graphs it is clear that velocities are approximately of the same order. The difference in velocity distribution could be attributed to the various dimensions that were assumed (e.g. the length of the shelves and the length of the roof vents). The temperature difference between the inside of the west spans and the outside for the greenhouse in the literature and the current CFD model are illustrated in Figure 7 and 8 respectively. It can be seen that the temperature distribution in the west spans are relatively homogeneous throughout. The temperature differences obtained for the CFD model is slightly lower than those obtained in the literature, but also fairly constant.

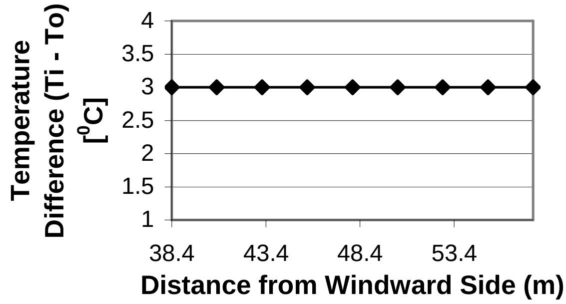

Figure 7: *Temperature Difference between inside (Ti) and Outside (To) for Greenhouse in Literature*

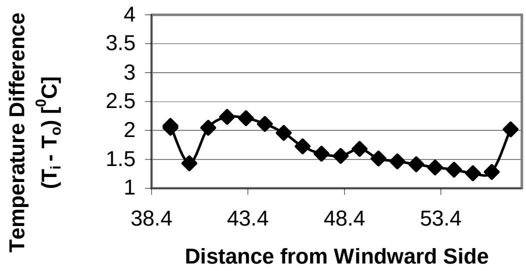

Figure 8: *Temperature Difference between inside (Ti) and outside (To) for the current CFD Greenhouse model.*

<u>Case 1: Full Partition</u>

In the first scenario, a partition wall has been inserted two divide the west span of the greenhouse into two distinct compartments. The partition wall was assumed to be manufactured from a 6mm thick [11] polycarbonate sheet [12], with a thermal conductivity of k = 0.21 W/m.K. The partition wall was modelled as a baffle in the CFD model. The temperature distribution is shown Figure 9 where a temperature of approximately 300K can be observed underneath the shelves in the right compartment. The velocity vectors are illustrated in Figure 10.

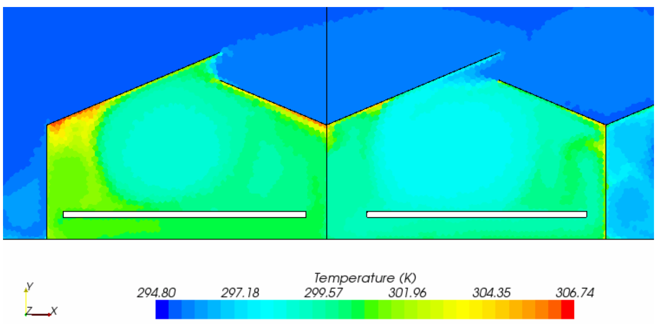

Figure 9: *Temperature Distribution in West Span (Case 1)*

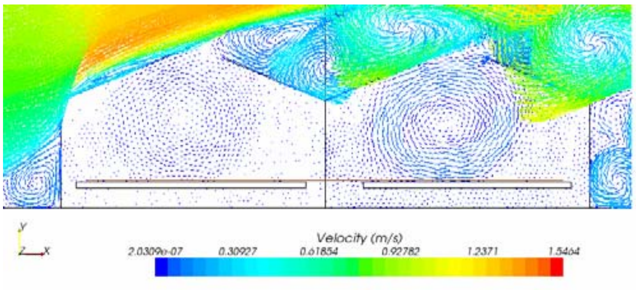

Figure 10: *Velocity Contours in the West Span for Case 1*

From Figure 10 it can clearly be seen that there is little to no movement at all within the west span, although two counter clockwise convective loops are formed within each individual compartment. The air current in the right compartment has a slightly higher velocity than the left side because of the temperature effect introduced by the plastic partition. Figure 11 shows that the velocity inside the partitioned greenhouse is fairly reduced compared to the velocities inside the open west span.

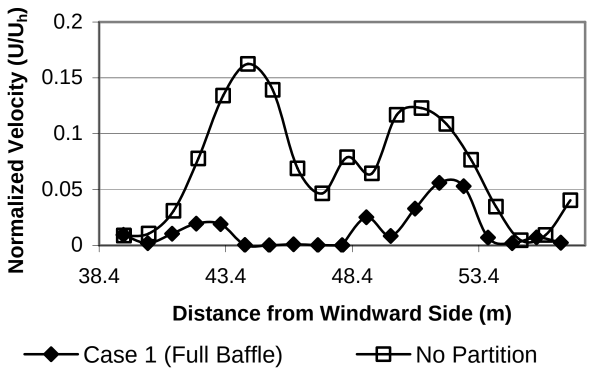

Figure 11: *Velocities for Open and Partitioned Greenhouse*

The temperature contour plot indicates that the temperature of the air inside the greenhouse is significantly higher (approximately 4.4°C) compared to the outside air, which can be attributed to the low air velocities. The difference in temperature is shown in Figure 12, which clearly indicates the temperature significantly rises as a result of the added partition.

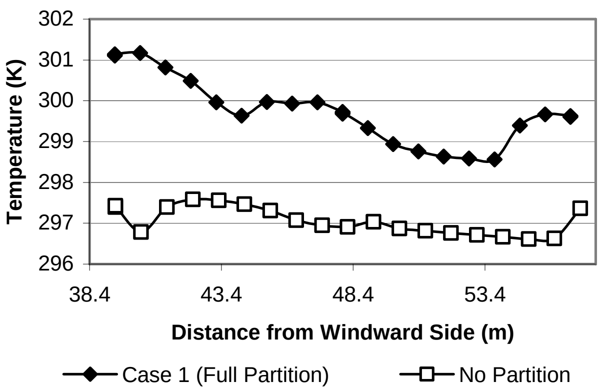

Figure 12: *Temperatures for Open and Partitioned Greenhouse*

Case 2: Half Partition

For this case, the height of the partition has been reduced to half the height of the full partition. The temperature contour plot is shown below in Figure 13 and a comparison to temperatures measured in the open greenhouse and the full partitioned greenhouse are illustrated in Figure 14.

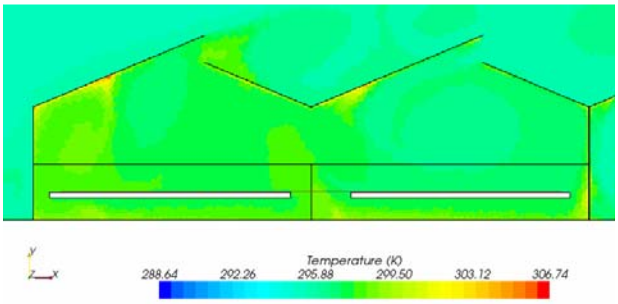

Figure 13: *Temperature Distribution in West Span (Case 2)*

From both figures it should be clear that the temperature is significantly lower compared to the temperatures in the full partitioned greenhouse, in the same order compared to the open greenhouse configuration. The temperature distribution is also more homogeneous compared to that of the full partitioned greenhouse.

The velocity vectors shown in Figures 15 illustrate the air currents inside the two west spans. Once again, two convective loops are formed, the loop on the right side having a slightly increased velocity.

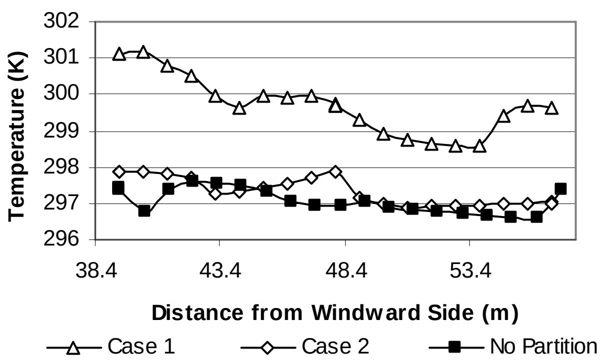

Figure 14*: Temperatures for Full Partition (Case 1), Half Partition (Case 2) and no Partition*

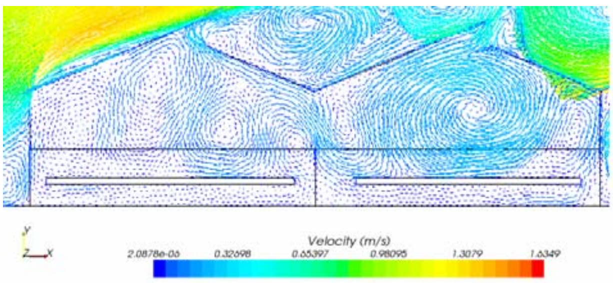

Figure 15: *Velocity Vectors in West Span (Case 2)*

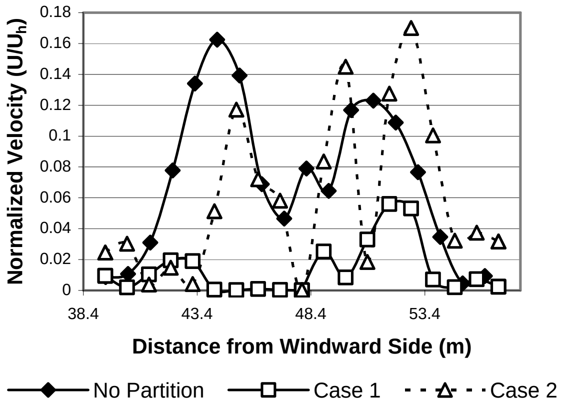

Figure 16: *Velocities for Full Partition (Case 1), Half Partition (Case 2) and no Partition*

Comparing both Case 1 and Case 2 with the open greenhouse, Figure 16 indicates that the lowest velocities occur inside the greenhouse with a full partition. The effect of partition height is clearly illustrated in Figure 16 where the normalized velocity varies from virtually zero to approximately 0.17.

CONCLUSION AND FUTURE RESEARCH

The effect of internal partitions on the internal flow of a greenhouse has been modelled with the use of Computational Fluid Dynamics. The model was first validated by comparing temperatures and velocities inside an open greenhouse. It was found that the velocities and temperatures of the climate inside the greenhouse were of the same magnitude as those in the literature. Discrepancies can be attributed to differences in greenhouse geometry.

Considering Case 1, where the west span of the greenhouse contains a full partition, the results of this study shows a significant drop in velocity and a considerable increase in temperature inside the individual compartments. The temperature distribution at plant level is more heterogeneous compared to that of the open greenhouse. Results for case with half a partition inserted indicated an influence on the velocities and temperatures to a lesser extent than that of the full partitioned greenhouse. The temperature distribution at plant level is also more homogeneous.

The current developed CFD Model could be useful in the design of the greenhouses, particularly the placement of partition walls and shelves.

Future research will focus on the characteristics of the greenhouse structure, such as different vent configurations and the optimum location for these vents. The turbulent character of the air flow will also be investigated in further detail. Fully unsteady, three-dimensional models will also be developed and the effect of radiation can be implemented.

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