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THE EFFECT OF BENCH ARRANGEMENTS ON THE INDOOR CLIMATE OF NATURALLY VENTILATED GREENHOUSES

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NOMENCLATURE

ρ	[kg/m^3]	Density
Φ	*	Scalar Quantity
V	[m/s]	Velocity
v_g	*	Grid Velocity
Γ	*	Diffusion Coefficient
A	*	Face Area
g	[m/s^2]	Gravitational Vector
G	*	Grid Flux Computed from mesh motion
S_Φ	[-]	Source Term
T_{ref}	[K]	Operating Temperature
β	[/K]	Coefficient of Bulk Expansion
Subscripts and Superscripts		
0	[-]	Cell Number
F	[-]	Face Quantity
V		Cell Volume

* For units refer to the StarCCM+ Documentation [1]

ABSTRACT

Greenhouses are used worldwide to effectively produce crops and flowers out of season by protecting them from adverse environmental factors [2]. High inputs (water, nutrients, plant protection chemicals, handling material and fossil energy) are required for this method of production, which may unfortunately lead to environmental problems [3]. Due to an increased interest in reducing energy consumption, natural ventilation has become a popular alternative method to control the indoor climate of greenhouses. Effective control of the indoor climate of greenhouses is of vital importance, as this directly influences the quality and quantity of the crop production. The purpose of this paper is to investigate the effect of bench arrangements on the internal environment in naturally ventilated Venlo-type greenhouses. The study will be conducted numerically, using computational fluid dynamics (CFD). Two-dimensional models will be created and a mesh sensitivity study will be conducted to determine a suitable mesh size. The effect of various bench arrangements used commonly in industry on the temperature and velocity distributions inside the greenhouses will be assessed. The case of a heated floor will be examined, with single, double and triple solid bench arrangements. A three-dimensional double span greenhouse will also be created containing four longitudinally arranged benches, and compared to a corresponding two-dimensional model. It was found that overall the wind direction and bench arrangements do have a significant effect on the microclimate at plant level, creating large velocity and temperature differences between the various bench arrangements.

INTRODUCTION

Development of environmental and sustainable agriculture has become one of the main objectives of agricultural research. The recent emphasis on energy saving has increased the popularity of the use of natural ventilation in commercial greenhouses. Ventilation in naturally ventilated greenhouses is driven by pressure differences created at intentional openings, such as roof and side vents. These pressure differences are caused by temperature differences between the inside and the outside of the greenhouse, commonly known as the buoyancy or stack effect, as well as outside wind effect [4]. Greenhouses are mainly used to protect plants from adverse environmental factors [2]. Greenhouse parameters such as air temperature, carbon dioxide supply and relative humidity are directly influenced by ventilation. The control of these parameters is crucial as they have an effect on the quality and quantity of the crop production. For example, maintaining the indoor temperature is of vital concern, as the temperature can exceed the optimal value and the crops might be damaged [5]. The development of diseases is also strongly related to the local humidity and temperature within the greenhouse. The use of pesticides could be reduced considerably by maintaining a uniform climate. This in turn will ensure that local conditions which are favourable for diseases are avoided [6]. A uniform climate might also assist in ease of harvesting by ensuring uniform product quality. Another important factor in commercial greenhouse is the efficient utilization of the space within the greenhouses, which is based on the maximum amount of growing area achieved [7]. To accomplish this, various raised bench arrangements are commonly used in multi-span greenhouses, such as longitudinal and peninsular arrangements. Movable benches are [8] also gaining popularity. Each type of arrangement has its advantages and disadvantages however. For example, the peninsular bench layout results in a greater growing area compared to longitudinal, but routine tasks such as watering become cumbersome with the longitudinal arrangement [7]. In order to improve the crop production, more detailed information is required about the microclimate inside the greenhouses

The indoor climate of greenhouses has been investigated for several decades. Initial studies in the 1950's focused on quantitative studies to investigate the possibility of increasing the commercial viability of these structures [5]. Advances in computer technology of the last decade have made it possible to use Computational Fluid Dynamics (CFD) to investigate the indoor climate of greenhouses. CFD is a useful technique for investigating spatial and temporal distributions inside greenhouses. Some of the earliest CFD investigations were conducted by Okushima et al [9].A thorough review on the applications of CFD in the modelling and design of ventilation systems in the agricultural industry was published by Norton et al [10]. It was found that the quality of the solutions is dependent on the chosen turbulence model. The author concluded that greenhouse investigations have generally been of a higher standard compared to animal housing, since crop biological models have been incorporated in the computational models. The indoor airflow has been investigated by several authors using CFD [11], [12], [13]. CFD has also been used to investigate the influence of various vents arrangements in greenhouses [12], [14], [15]. Previous work done by this author addresses inter alia the influence of internal partitions [16], time-varying boundary conditions [17] and three-dimensional effects due to varying wind direction [18] . Majdoubi et al [19] investigated experimentally and numerically the airflow and microclimatic patterns in a one-hectare Canary type greenhouse. Some of the conclusions were that temperature and humidity induced buoyancy forces create air loops which tend to improve the indoor climatic conditions. Sethi [20] compared the five most commonly used single span greenhouse shapes, and concluded that the most solar radiation is received by uneven span, while the quonset type receives the least. Ganguly et al [21] developed a model for predicting the performance of a floriculture greenhouse under natural ventilation. They concluded that the performance of a greenhouse under natural ventilation is influenced significantly by various parameters such as solar radiation, distance between roof vents and free wind speed. Work done by Shilo et al [22] also refers to experimental work that may be useful to calibrate future and current CFD studies in future papers. In this paper it will be attempted to investigate the flow patterns and instabilities developed inside a greenhouse due to various types of bench arrangements using two and three dimensional CFD models.

COMPUTATIONAL FLUID DYNAMICS

Introduction

Computational Fluid Dynamics (CFD) is a research and design tool, which can produce quantitative predictions of fluid flow. These predictions are based on the laws of conservation (mass, momentum and energy) [23]. Although computational fluid dynamics yields only approximate solutions, it has a number of advantages. The results can be produced at a relatively low cost and quickly. The solutions may provide detailed information about the variables throughout the flow field. It is also relatively simple to change the parameters of the domain of interest. CFD also enables the user to simulate both realistic and ideal conditions. In Computational Fluid Dynamics a numerical solution of partial differential equations, typically the Navier-Stokes equations are obtained [24]. These equations govern the transport of mass, momentum and energy in moving fluids. Three laws govern the transport of the above quantities: conservation of mass, Newton's second law of motion and the first law of thermodynamics [25]. 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 algebraic equations. An algebraic multi-grid solver is then used to solve the resulting equations [1]. To illustrate this, the transport of a simple scalar will be considered. The continuous integral form of the governing equation is typically given by [1]:

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

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 typically defined in the StarCCM+ documentation [1]. If Equation 1 is discretized, the following equation results:

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

A detailed description of a discretization procedure can be found in Patankar [26].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 in equation 3:

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

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 [1]. Previous investigations have indicated the turbulent nature of both the inner and outer flow in greenhouses [27]. 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 [28]. Additional terms have been added in StarCCM+ to account for buoyancy (in this case the Boussinesq approximation) and compressibility effects.

CFD model setup

The greenhouse is in this study is based on a greenhouse found in the literature [11] and have already previously been validated [16]. This greenhouse contained four spans (width, 4 by 9.60m; length, 68m; eaves' height, 3.90m; ridge height, 5.9m) and was covered by 4mm thick horticulture glass. The greenhouse roof was equipped with continuous roof vents on both sides of each span. Initially, two-dimensional models of this greenhouse consisting of a single span venlo-type greenhouse containing different bench arrangements were investigated with the roof ventilators opened towards the windward and leeward side. This greenhouse was also made of glass. The negative y direction was chosen as the direction of the gravitational constant for the further greenhouse models shown in this paper. The wind was modeled to act from left to right in an eastern direction at 1m/s. Figure 1 shows the two dimensional numerical models of the meshes for the various cases assessed.

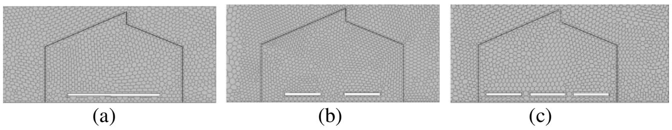


Figure 1: Bench Arrangements (Two Dimensional Leeward Facing Greenhouse): Single (a), Double (b) and Triple (c)

In order to investigate the three-dimensional effect of bench arrangements on the indoor climate, a three dimensional model of a double span greenhouse with two longitudinal benches in each span was also created, with a corresponding two-dimensional model. All the ventilators for these two models were opened towards the leeward side. This is shown in Figure 2 and 3 respectively. The geometry (seen in Figure 3) of the benches are slightly different in order to compare the results with the ongoing experimental work, which initially will contain closed benches.

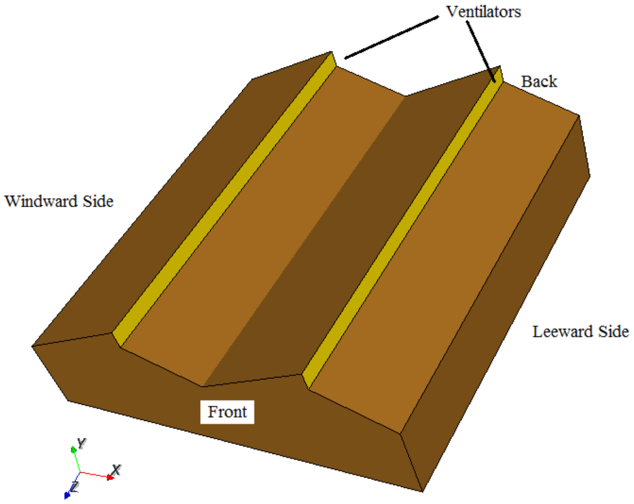


Figure 2: Three-dimensional Model

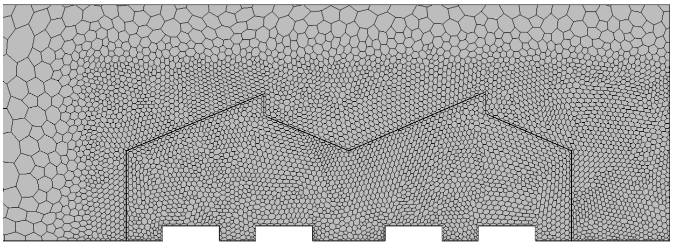
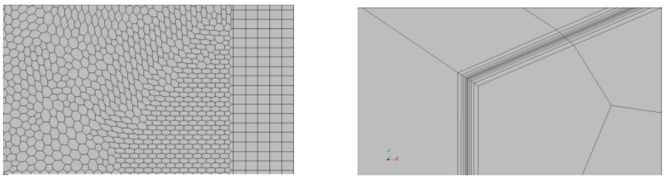


Figure 3: Corresponding Two-dimensional model Containing Four Longitudinally Arranged Benches

During the experimental period in the original article, ornamental 0.2m high plants were grown on shelves, but since they were small plants with a low transpiration rate, their presence was ignored in the numerical analysis. The length of the shelves was assumed, and the ventilator openings were assumed to be 1.22m wide [2]. Simulations on the current greenhouse were done using the StarCCM+ solver [1]. To minimize the amount of cells, each glass wall and the roof were modelled as a baffle with an appropriate thermal resistance. A large control volume (200m×100m) was created around the greenhouses in order to minimize interference with the flow inside the greenhouse and to allow for development and definition of the boundary layer. The outlet of the domain was specified as a porous region, using the mesh extruder in StarCCM+ in order to force the flow out of the domain. The porous region consisted of orthogonal extruded cells, which was extruded from the volume mesh at the outlet boundary (Figure 4a). The extruded mesh consisted of 5 layers, with an extrusion length of 5m. Before the final mesh was created, the mesh around the greenhouse was refined (Figure 4b) using a brick-shaped volume shape with a relative size of 6% of the chosen base size.



(a) (b)

Figure 4a & b: Extruded Mesh and Prism Layer Mesh on Wall-type Boundaries

The domain was meshed using a polyhedral meshing model, together with a boundary layer meshing model. The prism layer model was activated to ensure adequate modeling of the flow in the boundary layer. The prism layer mesh consisted of 5 orthogonal prismatic cells, with a combined relative thickness of 0.25% of the chosen base size. The prism layer was present on all the wall-type boundaries in the solution domain. A tetrahedral mesh was created initially, after which a special dualization scheme was implemented to generate the polyhedral mesh, which consists of arbitrary shaped polyhedral cells.

Once the three-dimensional mesh had been created, the mesh was converted to a two-dimensional mesh to reduce computational running time [11] for the initial simulations. Monitor points were inserted at various points to examine the progress of the solution. A line probe was inserted at 1m level to obtain the numerical velocity and temperature distribution at plant level. As an initial solution, steady, laminar conditions were assumed together with segregated energy model. After 1000 iterations, turbulence and gravity activated. A heat flux of 47.5W/m² was imposed on the floor of the greenhouse. This value is based on a value used in a previous study [29]. This value is based on hourly solar radiation data for Nelspruit in the province of Mpumalanga [30]. It was assumed that 50% of the solar radiation emitted through the glass covering was re-emitted from the ground [31]. The results indicated poor convergence, as well as an inherently transient flow. Lastly, the implicit unsteady solver was activated, with the appropriate time step to ensure a Convective Courant number smaller than 1 inside the greenhouse. StarCCM+ employs the SIMPLE algorithm to control the overall solution. More details on this algorithm can be found in the StarCCM+ Manuals [1] and Patankar [26].

RESULTS

The steady state results from the CFD simulations are presented in the form of parametric charts and contour plots. Initially three two-dimensional cases were run, and lastly a three-dimensional steady state case containing longitudinal benches was also investigated. This was in order to determine the three-dimensional effect of the bench arrangements on the flow field at plant level. All the values of the parametric plots were taken at plant level (1m above the floor of the greenhouse).

In order to conduct a mesh sensitivity analysis, all the relevant mesh parameters were specified relative to the chosen base size. The base size was then varied to obtain different meshes. The mesh sensitivity study was conducted to determine a suitable mesh size for the simulations. Table 1 shows the results of the mesh sensitivity analysis and a plot of velocity versus number of cells can be seen in Figure 5.

Table 1 : Mesh Sensitivity Analysis Results (Triple Bench)

Base Size (m)	Nr of Cells	Velocity Monitor
3		0.370
3.5	47252	0.406
3.8	38091	0.392
4	35091	0.385
4.5	28896	0.366

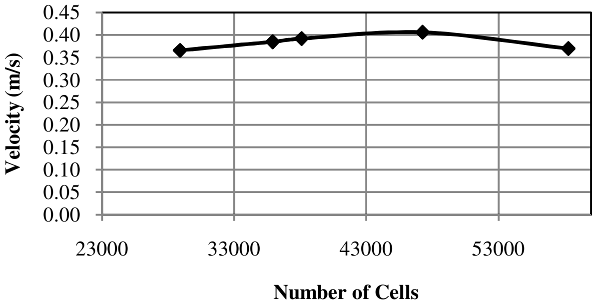


Figure 5: Number of Cells vs. Velocity Monitor

Figure 5 indicates that the values increase as the base size is decreased. A maximum value is reached for a base size of 3.5m, after which the velocity starts to decrease again. It seems as if an optimum base size to use for the mesh would be around 3.5m. This was the chosen base size for all the simulations.

The following cases were investigated numerically for both leeward and windward opened ventilators:
<u>Case 1:</u> A single bench
<u>Case 2:</u> Two benches
<u>Case 3:</u> Three benches
Case 4: A three-dimensional double span greenhouse containing two longitudinal benches in each span were created, and compared to a corresponding two-dimensional model.

Case 1: Single Bench Arrangement

The Vector plots are shown in Figure 6. The direction of flow could be deduced by closer inspection. For both configurations, large convective cells formed inside. The cell is rotating anti-clockwise for the windward opened ventilators, and clockwise for the leeward opened ventilators. For both configurations, the air is sucked into the greenhouse at the bottom of the ventilator, and blown out at the top. Figure 7 and 8 represents the temperature and velocity contour plots respectively for both the windward and leeward facing greenhouse containing a single bench. The results of the line probe inserted at plant level are graphed in Figure 9. It can be seen that the same trend is followed with the velocity distribution, and approximately the same maximum velocity is reached at the centre of the bench (approximately 0.5 m/s). The most notable difference can be seen close to the front and back of the greenhouse.

At the front of the greenhouse, the velocity is 0.11 m/s lower for the leeward ventilator greenhouse, whereas the opposite occurs at the back of the greenhouse. Here the windward ventilator greenhouse has a velocity of 0.08 m/s lower compared to the leeward facing greenhouse.

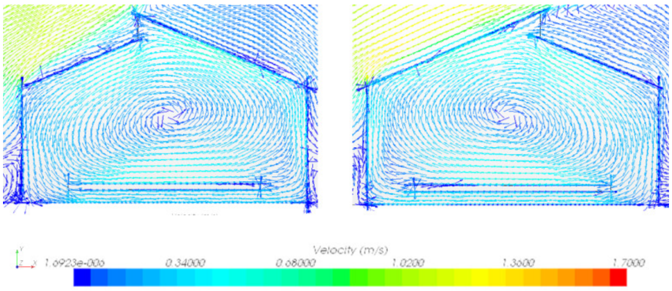


Figure 6: Case 1 - Vector Plots for Windward and Leeward Opened Ventilators

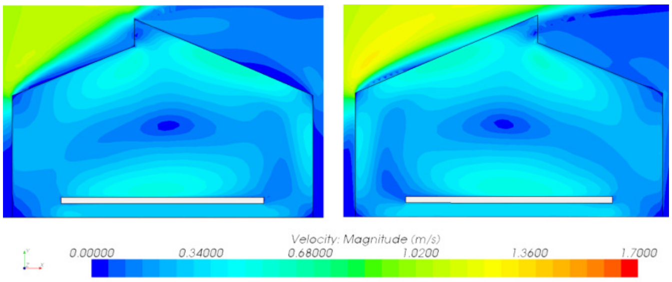


Figure 7: Case 1 - Velocity Contour Plot (Windward and Leeward Facing)

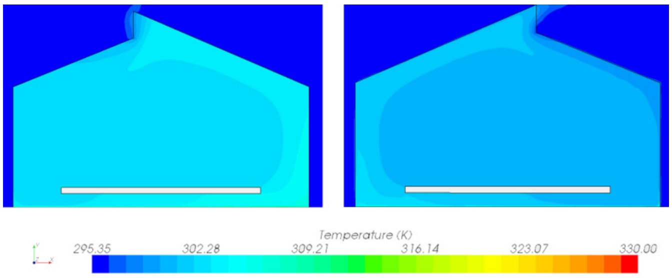


Figure 8: Case 1 - Temperature Contour Plot (Windward and Leeward Facing)

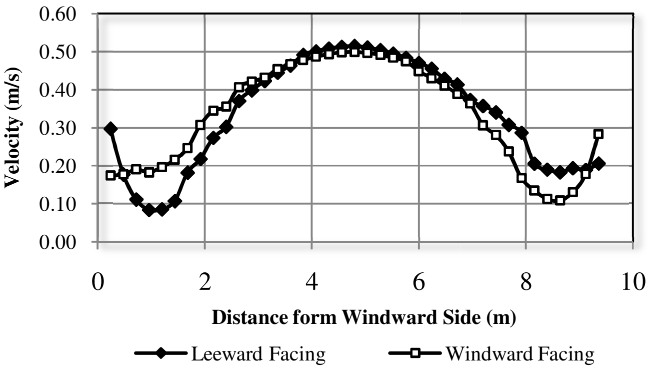


Figure 9: Case 1 - Comparison of Velocity Distribution at plant level (1m)

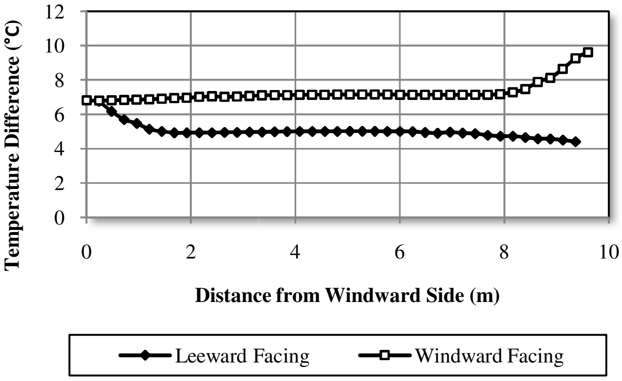


Figure 10: Case 1 - Comparison of Difference in Temperature Distribution at plant level (1m)

Figure 10 illustrates the difference between the inside and ambient temperature across the bench. Both show a homogeneous distribution and a similar temperature close to the front of the greenhouse, but the temperature distribution is quite diverse for the two configurations. The configuration with the windward opened ventilator is on average 7.3 degrees hotter above the shelve compared to the outside, and the temperature increases towards the back of the greenhouse, where a maximum of about 304 Kelvin (31°C) is reached. The Leeward facing greenhouse has a lower temperature difference of 5 degrees, with the temperature dropping to approximately 27°C at the back of the greenhouse. These temperatures are nevertheless quite high and indicate that ventilation might be insufficient.

Case 2: Double Bench Arrangement

The vector plots for Case 2 are shown in Figure 11. The same scenario can be seen as in Case 1. Both contain large convective cells moving in opposite directions for the two ventilator configurations. Areas of no air movement are also visible on the first (Windward) and second shelves (Leeward).

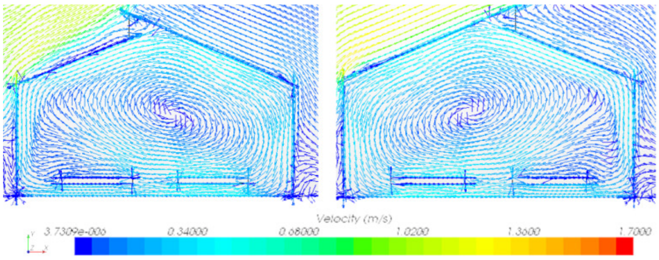


Figure 11: Case 2 - Vector Plots for Windward and Leeward Opened Ventilators

The velocity and temperature contour plots are shown in Figures 12 and 13 respectively. The contours display a non-uniform velocity distribution. The velocity and temperature measured at plant level for the double bench arrangement can be seen in Figures 14 and 15 respectively. For both configurations the velocity and temperature distributions are almost mirror images of each another. The velocity distribution for both windward and leeward ventilator greenhouses is heterogeneous, ranging from areas where there is virtually no movement, to areas with a velocity of 0.38 m/s in the centres of the front and back shelves. The temperature distribution is homogenous and relatively similar. Across the most of the two benches, the temperature difference is approximately 9 degrees (absolute temperature of about 31°C) between the inside and outside, with the temperature for the windward facing greenhouse decreasing from 33.4°C to 31.2°C towards the back of the greenhouse, while the opposite trend is visible for the leeward facing greenhouse.

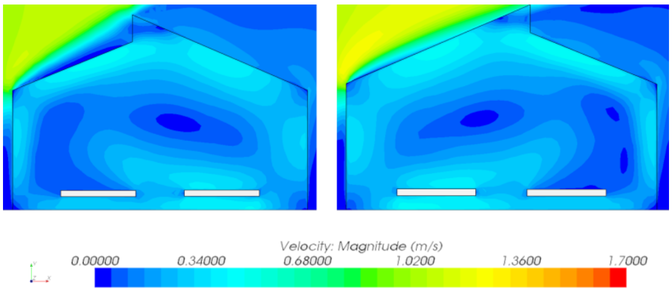


Figure 12: Case 2 - Velocity Contour Plot (Windward and Leeward Facing)

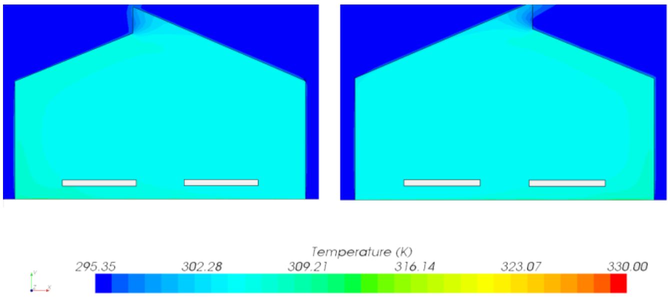


Figure 13: Case 2 - Temperature Contour Plot (Windward and Leeward Facing)

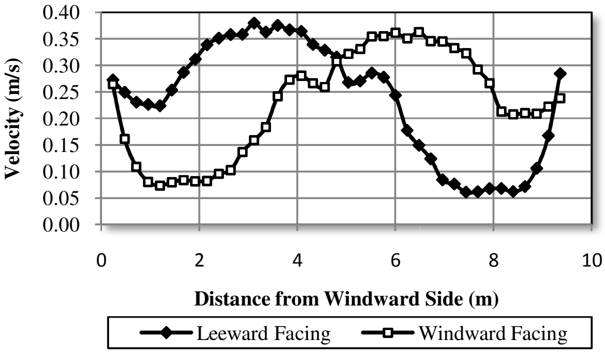


Figure 14: Case 2 - Comparison of Velocity Distribution at plant level (1m)

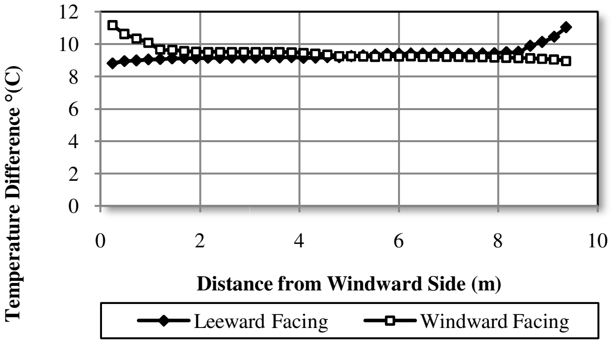


Figure 15: Case 2 - Comparison of Temperature Distribution at plant level (1m)

Case 3: Triple Bench Arrangement

Figure 16 illustrates the vector plots for the triple bench arrangement, while the contour plots are shown in Figures 17 and 18. Both greenhouses contain a single convective cell rotating in the same direction, with low velocities across the third bench.

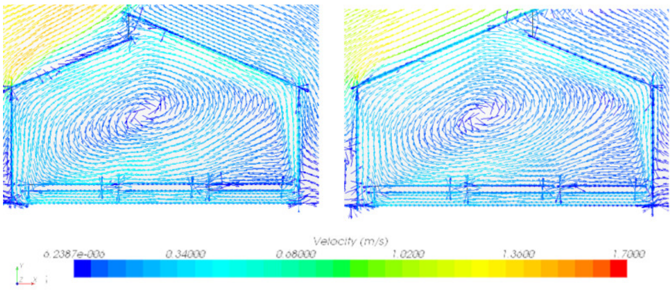


Figure 16: Case 3 - Vector Plots for Windward and Leeward Opened Ventilators

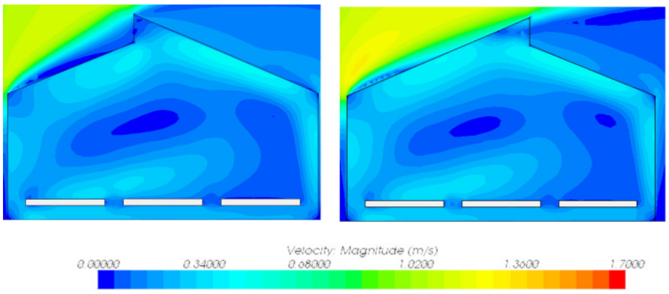


Figure 17: Case 3 - Velocity Contour Plot (Windward and Leeward Facing)

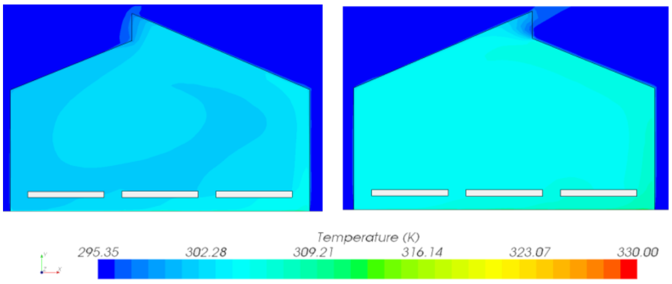


Figure 18: Case 3 - Temperature Contour Plot (Windward and Leeward Facing)

Figure 19 and 20 plots the line probe results at plant level. Both the velocity and temperature distribution follows much the same trend, the velocities are high (approximately 0.35 m/s) compared to the back half of the greenhouse, where there virtually no air movement across the third shelve. Temperature distributions are relatively homogeneous, although the leeward opened ventilators results in a higher temperature difference (about 9.4 degrees) across the width of the greenhouse, and even higher in the vicinity of the back wall.

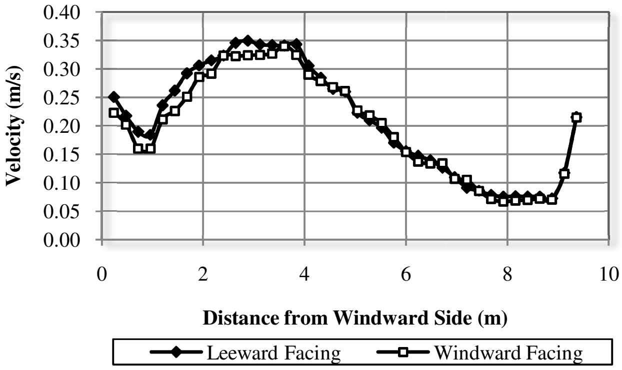


Figure 19: Case 3 - Comparison of Velocity Distribution at plant level (1m)

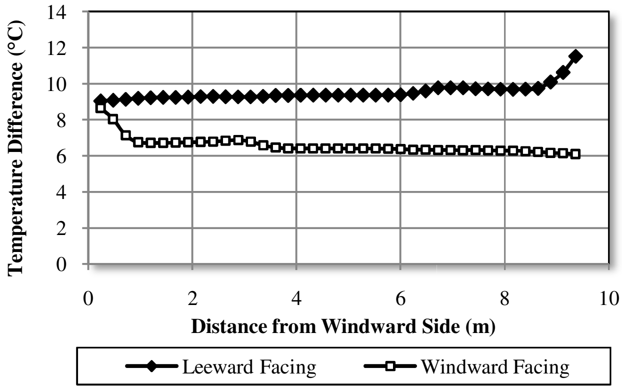


Figure 20: Case 3 - Comparison of Temperature Difference at plant level (1m)

Figure 21 and 22 compares the velocity and temperature distribution at plant level for all three bench arrangements with a leeward opened ventilator. All three demonstrate heterogeneous behaviour. The single bench arrangement (Case 1) results in a maximum velocity of approximately 0.51 m/s in the centre of the bench. The other two bench arrangements reach a lower maximum value of about 0.34 m/s closer towards the front of the greenhouse. These conditions can be detrimental to the crops inside, as this will result in non-uniform crop production and quality.

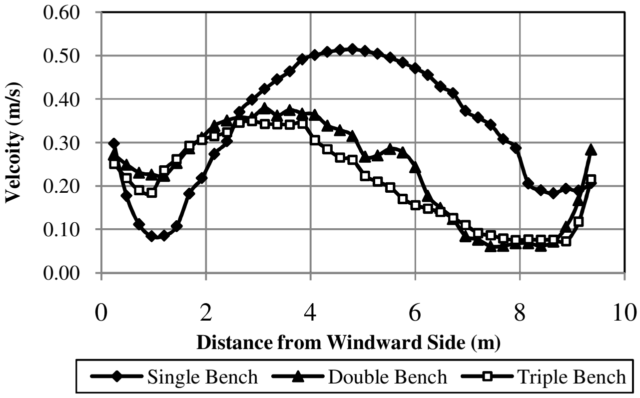


Figure 21: Comparison of Velocity Distribution for Case 1, 2 and 3 (Leeward Facing)

The single bench arrangement exhibits the lowest temperature distribution with an average of 5°C difference between the inside and outside of the greenhouse, whereas Case 2 and 3 due to the lower air velocity has a much higher temperature distribution at plant level. The difference for these two cases between the inside and outside is approximately 9°C. The absolute temperature across most the width of the greenhouse for the last two cases is about 32°C which is quite an elevated temperature. This is undesirable to certain crop species, as the crops might start to wilt, especially in the region of the back wall.

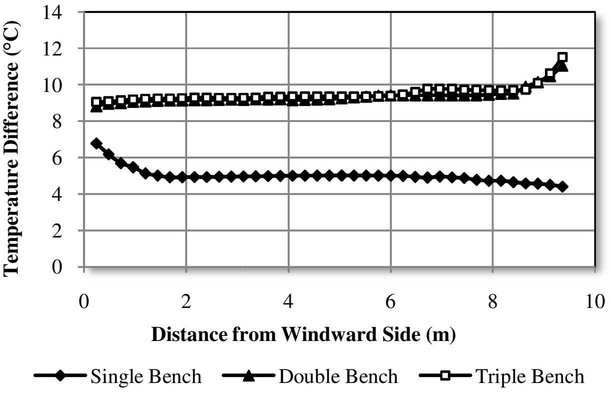


Figure 22: Comparison of Temperature Distribution for Case 1, 2 and 3 (Leeward Facing)

The velocities and temperatures at plant level are compared in Figures 23 and 24 respectively for the windward opened ventilators/facing greenhouse. All three bench arrangements results in a heterogeneous velocity distribution at plant level. Figure 23 shows that a maximum velocity is reached in different locations for each type of bench arrangement, and that all three bench arrangements results in a non-uniform velocity distribution at plant level. Figure 24 depicts a uniform temperature distribution at plant level, with the double bench arrangement displaying the largest difference in temperatures between inside and outside.

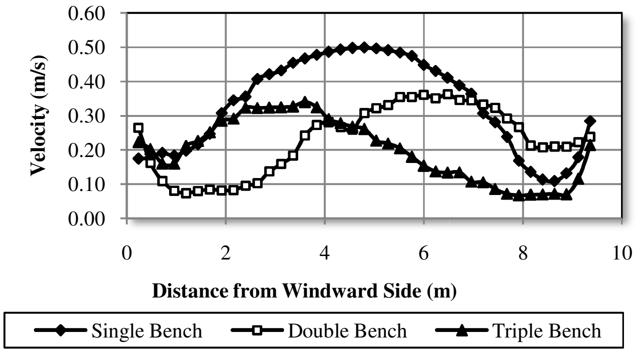


Figure 23: Comparison of Velocity Distribution for Case 1,2 and 3 (Windward Facing)

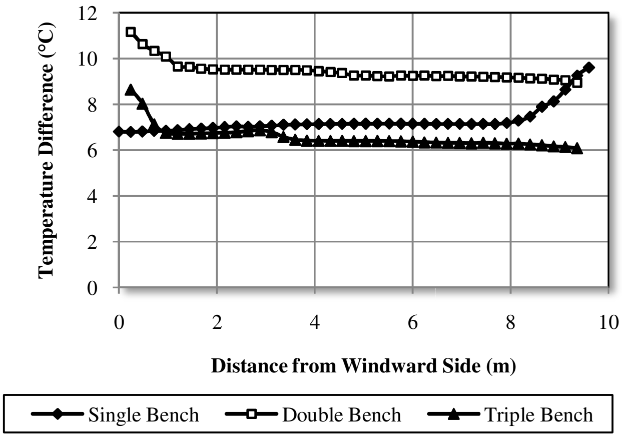


Figure 24: Comparison of Temperature Distribution for Case 1,2 and 3 (Windward Facing)

Case 4: Comparison of Two Span 2D and 3D Model

Lastly a three-dimensional model and corresponding two-dimensional model containing four benches arranged longitudinally were created in order to determine the three dimensional effect. The vector plots obtained from the simulations are shown in Figure 25 and 26.

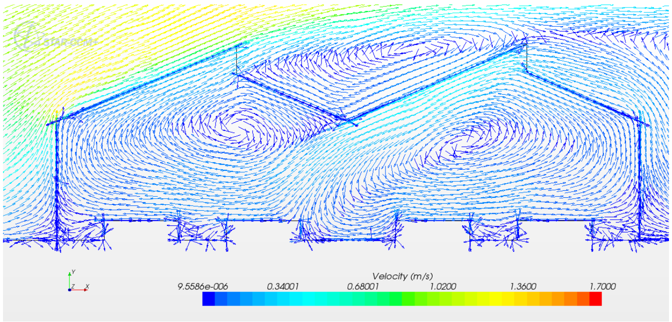


Figure 25: Vector Plot for Double Span Greenhouse

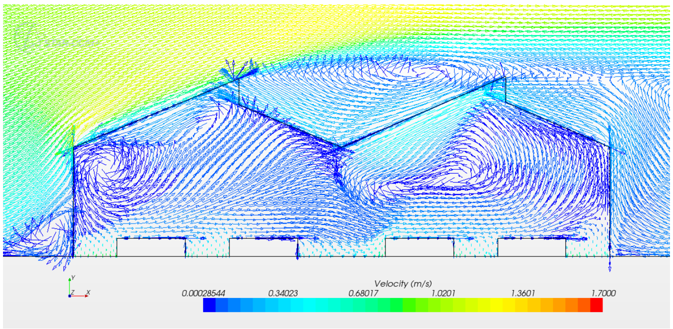


Figure 26: Vector Plot for Double Span Three-dimensional Greenhouse (Centre)

Comparing the two vector plots, it can be seen that the convective cells inside are quite different. The two-dimensional plot contains two large cells, whereas the three-dimensional plot contains at least four separate cells.

The velocity and temperature contour plots can be seen in Figures 27 and 28 respectively. The 2D model was compared to a section taken in the centre of the 3D model. At a glance, it can be seen that the velocity contours are dissimilar. The temperature distributions are also different. It seems as if the three-dimensional model conveys a much more uniform overall temperature distribution.

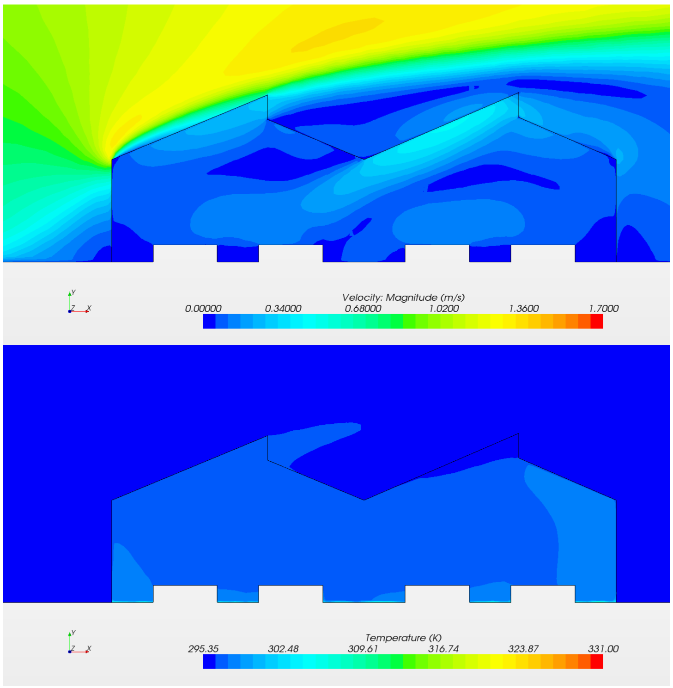


Figure 27: Double Span Two-Dimensional Velocity and Temperature Contour Plot

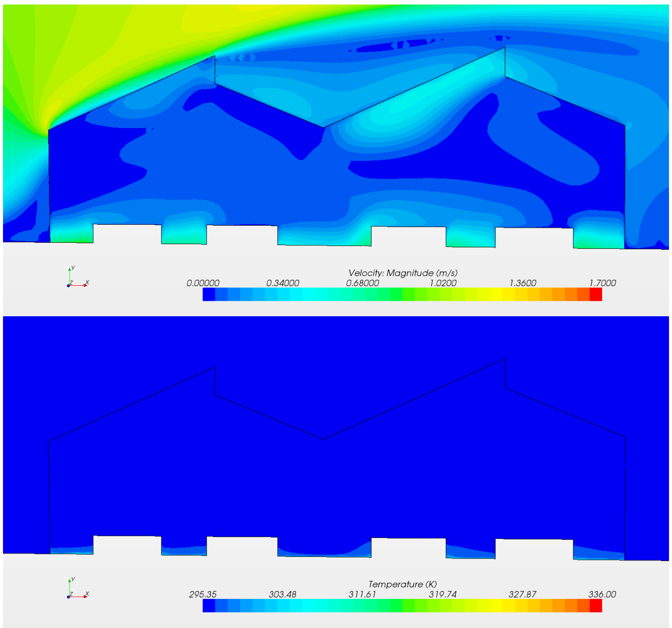


Figure 28: Velocity and Temperature Contour Plot (Centre of 3D Greenhouse)

Figure 29 plots the velocity distribution at plant level for both models, and from the graph it is seen that there is quite a difference in velocity distribution. Both distributions are heterogeneous, but overall the two-dimensional model exhibits lower velocities across the benches. The maximum velocity in the 2D model is 0.15 m/s, whereas the maximum velocity of 0.32 m/s is reached above the third bench.

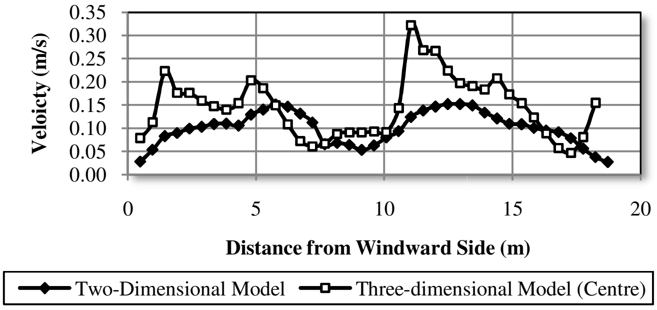


Figure 29: Comparison of 2D and 3D (Centre) Velocity Distribution

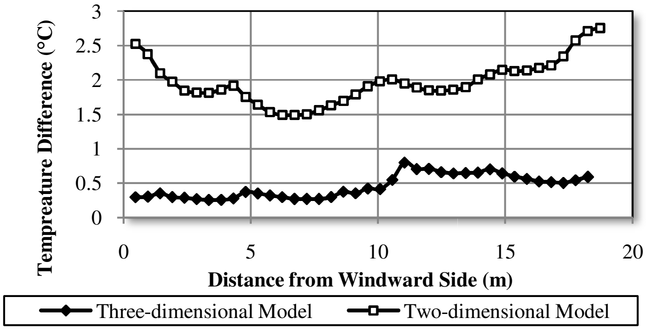


Figure 30: Comparison of 2D and 3D (Centre) Temperature Distribution

Lastly, Figure 30 shows the temperature distribution taken at plant level. The three dimensional model conveys a lower overall temperature across the benches compared to the two-dimensional model, and the temperature distribution in also slightly more homogeneous. It can therefore be seen that three-dimensional effects are present in these large greenhouses and needs to be investigated further.

CONCLUSION

In this paper, CFD models of a greenhouse were used to investigate the indoor climate of greenhouses containing various bench various bench arrangements (single, double and triple) subject to two different wind directions. For all three two-dimensional cases, it was found that the number of benches does have a significant effect on the climate at plant level. The influence of the wind direction can also be seen from the line probe plots, where conditions in the greenhouse are sometimes mirror-images, but reversed. The average temperature at plant level is rather high, and it seems as if roof ventilators alone might not be sufficient to ventilate this type of greenhouse. This study indicates that care should be taken when placing benches close to the walls of the naturally ventilated greenhouse, as there is quite a significant increase in temperature in these areas. This parametric investigation shows the importance of using CFD simulations to determine the effect of various parameters such as wind direction and bench arrangements on the microclimate at plant level. Current results were generated as part of an exploratory research study on the effect of bench arrangements and three-dimensional effects in greenhouse microclimates. Future research will focus on the three-dimensional case,. An in-depth mesh sensitivity study will conducted. The possibility of adding side ventilators, the influence of wind direction as well as other types of bench arrangements will be investigated. The results will be investigated and discussed in detail.

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