NUMERICAL INVESTIGATION OF A NATURALLY VENTILATED GREENHOUSE CONTAINING STACKED BENCHES

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ABSTRACT

The rapidly growing concerns of energy efficient methods have increased the emphasis on natural air ventilation in indoor environments such as greenhouses. Naturally ventilated greenhouses are used to create a microclimate that does not fluctuate majorly with the ambient conditions. This microclimate is of vital importance since it directly influences the quality and quantity of crop production. This study investigates the natural ventilation in a single-span greenhouse with a roof vent opening configuration using a two-dimensional Computational Fluid Dynamics (CFD) model. The numerical model is first successfully validated against data found in a study by Ould Khaoua. The two benches are then replaced by stacked type benches in order to investigate its effect on the indoor climate inside the greenhouse, which is the main objective of this study. The temperature and velocity profiles at the various stack heights were observed and it is noted that the temperature distributions are not significantly affected by the type of benches. However, the air velocity values are seen to be significantly lower for the lower racks when stacked benches are used. This indicates that care should be taken when placing plants on the lower racks as this could lead to non-uniform crop production.

INTRODUCTION

Air exchange between the interior and exterior environment of a greenhouse is of vital importance to ensure an optimum greenhouse microclimate. This air exchange is achieved by the implementation of a ventilation system [1]. A working ventilation system ensures that the relative humidity and CO_2 (Carbon Dioxide) levels are kept at an acceptable range by promoting the exchange of air thus preventing high temperature build up around the crops during excessive solar radiation conditions [2], [3].

Although high temperature conditions are generally required in greenhouses, excessive temperature build-up of above 32℃ can lead to moisture stress in plants [4]. This can result in the plants wilting and impede their growth. Moisture stress can also be caused by high wind speeds. The relative humidity being higher than the acceptable level can cause fungus spores to germinate in plants [3]. Due to these reasons, ventilation becomes of even more importance in greenhouses. Ventilation can be provided by natural means through purposely built vents and/or openings or through the use of external forces such as fans. Natural methods are being preferred as compared to the use of mechanical methods that require an external energy in order to minimise the use of non-renewable resources. In addition to being economical, another advantage of natural ventilation is that it tends to provide uniform conditions [5]. There are several parameters involved with regards to natural ventilations such as: temperature difference between the outside and inside ground, wind characteristics, the presence of cultivated plants and the type of benches present [4] [6]. Due to these factors, researchers are faced with enduring challenges in predicting the air flow patterns within the naturally ventilated greenhouse. As a result naturally ventilated greenhouses are also those where an external natural wind condition such as for example 1 m/s as considered in this paper is encountered.

Over the past years, several approaches have been utilized to investigate and predict the air flow patterns and microclimate inside greenhouses. CFD (Computational Fluid Dynamics) is a widely used advanced tool used for this purpose. CFD has been used in several research studies to investigate the flow in various types of naturally ventilated greenhouses. Fatnassi et al [7] investigated the distributed climate in a multi-span greenhouse. The research found that the interior temperature can be up to 10℃ higher than that of the exterior temperature and the CFD model showed agreement to this. Boulard et al [8] used a reduced scale greenhouse model to characterise the air fluxes induced in a naturally ventilated mono-span greenhouse. It was found that the air stream entering through the lower sections of the openings formed a large convective loop as distributed in the greenhouse and escaped through the upper sections of the openings; the developed CFD model showed agreement to this. Ould Khaoua et al [9] used CFD to analyse the ventilation efficiency of a multi-span greenhouse. The investigation was conducted over different ventilation configurations of roof vent opening, side vent openings and a combination of both. It was found that the ventilation efficiency showed a significant increase with orienting the roof vents windward. The greenhouse investigated contained single level benches.

There are various types of benches available for greenhouses. Single level desk type benches are most commonly used. Other types of benches include stacked type benches, step type benches and spiral level benches. The growth of the plants being places on these benches could be influenced by the presence of other plants (above or below) or a rack acting as an obstruction in the flow.

The objective of the current study is to investigate the effect of stacked type benches as compared to single level benches. The initial greenhouse geometry containing single level benches was evaluated against the experimental results found in the studies by Ould Khaoua [9].

NOMENCLATURE

m_{in}	*Mass into the system (kg)*
m_{out}	*Mass out of the system (kg)*
ρ	*Density (kg/m^3)*
U/u	*Flow Velocity (x direction) (m/s)*
v	*Flow Velocity (y direction) (m/s)*
w	*Flow Velocity (z direction) (m/s)*
g	*Gravitational Acceleration (m/s^2)*
C	*Constant*
T	*Temperature (℃)*
t	*Time (s)*
x	*Position (m)*
P	*Pressure (Pa)*
$\mathbf{u}$	*Velocity Vector (m/s)*
$S_{MX}/ S_{MY}/ S_{MZ}$	*Transport equations*

Ould Khaoua et al [9] investigated various ventilation configurations of two roof ventilation openings, one leeward roof ventilation opening and one windward roof ventilation opening in a four-span greenhouse [9]. Impact on air flow and temperature patterns inside the greenhouse due to these configurations were investigated. The greenhouse was N-S oriented covering an area of 2500 m^2. Dimensions of the greenhouse were as follows: 9.6 m width; 68 m length; 3.9 m eves height; 5.9 m ridge height and covered with a 4 mm thick horticulture glass. The first two spans contained single level plant benches of 0.75 m height with ornamental 0.2 m high plants. A plastic partition separated the two compartments of the greenhouse. Experimental testing was conducted, and the results used to create a numerical model. The current study will be focusing on the leeward roof ventilation configuration in the two left spans of the greenhouse [9]. Figure 1 shows a schematic view of the greenhouse in this configuration.

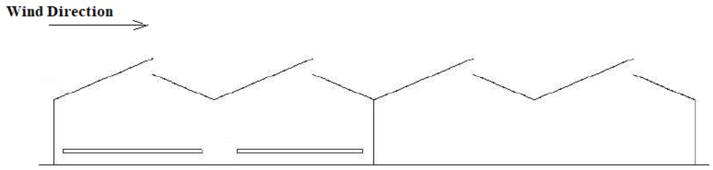

Figure 1 Schematic view of greenhouse with one leeward roof ventilation opening

The physical conditions which were used as input values and boundary conditions for the numerical model is shown in Table 1.

COMPUTATIONAL FLUID DYNAMICS (CFD)

Airflow patterns are calculated in CFD by solving transport equations, that are derived with the assumption that mass, momentum and energy are conserved in the continuum (Equation 1, 2 and 3) [10]. There are various methods that could be utilized to solve these transport equations which include the finite volume method, finite difference method and finite element method. StarCCM+ is the commercial software package that was used to simulate the greenhouse microclimate, this package is based on the finite volume method. The method subdivides the solution domain into a finite number of smaller control volumes corresponding to the cells of a computational grid.

Table 1 Input Values of Numerical model [9]

Parameter	Value
Inlet air velocity at 6 m	1.4 m/s
Inlet Temperature	22.2℃
Density	1.2 kg/m^3
Viscosity	1.51 × 10^{-5} kg/ms
Gravitational acceleration	9.81 m/s^2
Specific heat	100591 J/kgK
Thermal conductivity	0.0258 W/mK
Molecular weight (dry air)	28.9 kg/kmol
Atmospheric pressure	101.325 Pa
Outside ground temperature	27.9℃
Inside ground temperature	27.3℃
Glass wall temperature	29.1℃
Plastic partition temperature	31.3℃
Roof temperature	33.6℃

Continuum transport equations are then applied to each control volume in an integral form. A set of algebraic equations are obtained through this that are further solved [10].

$$\frac{dM}{dt} = \dot{m_{in}} - \dot{m_{out}} \tag{1}$$

$$\rho \frac{\partial U_i}{\partial t} + \rho U_i \frac{\partial U_i}{\partial x_i} = -\frac{\partial P}{\partial x_j} - \frac{\partial x_{ij}}{\partial x_i} + \rho g_j \tag{2}$$

$$pC\frac{\partial T}{\partial t} + \rho C U_i \frac{\partial T}{\partial x_i} = -P\frac{\partial U_i}{\partial x_i} + \lambda \frac{\partial^2 T}{\partial x_i^2} - T_{ij}\frac{\partial U_j}{\partial x_i} \tag{3}$$

Conservation of momentum equation (Equation 2) can be further written in terms of x, y and z co-ordinates; which are collectively known as the Navier-Stokes (Equation 4, 5 and 6). These equations are extremely useful in solving a wide variety of fluid flow problems and are considered the governing equations for compressible Newtonian fluid flow problems.

$$\frac{\partial(\rho u)}{\partial t} + \mathrm{div}(\rho u \mathbf{u}) = -\frac{\partial p}{\partial x} + \mathrm{div}(\mu \ \mathrm{grad}\ u) + S_{Mx} \tag{4}$$

$$\frac{\partial(\rho v)}{\partial t} + \mathrm{div}(\rho v \mathbf{u}) = -\frac{\partial p}{\partial y} + \mathrm{div}(\mu \ \mathrm{grad}\ v) + S_{My} \tag{5}$$

$$\frac{\partial(\rho w)}{\partial t} + \mathrm{div}(\rho w \mathbf{u}) = -\frac{\partial p}{\partial z} + \mathrm{div}(\mu \ \mathrm{grad}\ w) + S_{Mz} \tag{6}$$

The finite volume method begins the process by first performing the integration of the governing equations over the divided control volumes that are not over-lapping with one another. Since the method is based on the direct discretization of conservation laws; mass, momentum and energy are conserved.

The special discretization is conducted directly on the physical space due to which transformation problems between the co-ordinate systems are eliminated.

NUMERICAL MODEL

The greenhouse described previously from the data obtained from the study by Ould Khaoua [9] was used for comparison purposes to construct the numerical model. The geometry was created in Solidworks and imported into StarCCM+ as a Parasolid file. The ornamental plants present in the greenhouse were of relatively small size and therefore had a low transpiration rate due to which their effect on the flow was ignored. The study by Ould Khaoua [9] describes the wind being approximately perpendicular to the main axis of the greenhouse at the time of the experimental testing, the end wall effects may therefore be ignored, and thus the simulations are conducted two-dimensional. The two-dimensional simulation also reduces the computational running time and at this stage of the research on of the aims was to compare at least qualitatively between bench types..

Flow interference in the immediate vicinity of the greenhouse could be encountered which could affect the airflow pattern obtained inside the greenhouse. In order to avoid this scenario, a large control volume was created around the greenhouse. This control volume also acts as the atmospheric boundary layer around the greenhouse with the outflow section defined far downstream. In order to ensure there is no back-flow taking place, the outlet section of the domain was further specified to be a porous region (using the mesh extrude function in StarCCM+). The control volume was constructed of rectangular shape and with dimensions of 334 m × 160 m. A polyhedral mesh was generated for the solution domain together with a boundary layer meshing mode, while adequate modeling of turbulence in the boundary layer was ensure through the prism layer meshing model. The mesh was refined around the greenhouse area using a block type volume shape. Figure 2 shows this refined mesh.

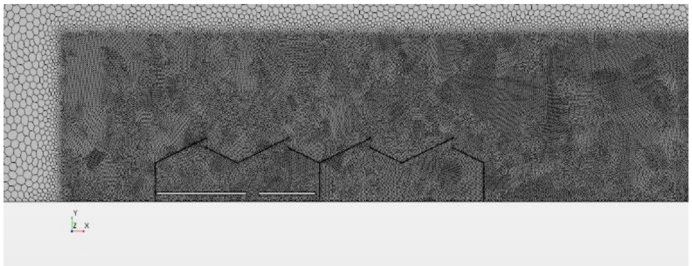

Figure 2 Refined mesh around greenhouse

The prism layer thickness was set to an absolute size of 0.01 m with 10 prism layers. A base size of 3.5 m was chosen after conducting a mesh sensitivity analysis, the remaining mesh parameters were left at the default values. The volumetric control function was utilized to refine the mesh around the greenhouse to a value of 4% relative to the base size. Extrusion from the outlet was a 10 m region with 10 orthogonal extruded cells. Thereafter the three-dimensional mesh was converted to a two-dimensional mesh. Wind as a natural external condition was modeled to act in an eastern direction (from left to right) at a speed of 1 m/s and gravitational acceleration to act in the negative y direction. The flow was initially run with steady, laminar conditions without activating gravity. Turbulence and gravity were then introduced in the CFD simulation, and gravity gradually increased to 9.81 m/s^2. The all y+ wall treatment was used, a requirement of this all y+ wall treatment is that the y+ values must be between 1 and 30; therefore this was ensured. The process was repeated with the same conditions and mesh parameters for stacked type benches once the simulation was successfully validated against the results from Ould Khaoua et al [9] that considered on single benches as shown in figure 1. Figure 3 shows an image of the geometry used for the stacked type benches with the dimensions given in mm. The total height of the bench is 1.8 m with 1.5 m width and racks of 0.1 m and central piece width of 0.05 m.

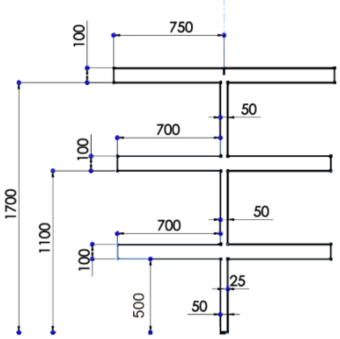

Figure 3 Stacked type bench geometry

Four sets of these stacked type benches were placed in the greenhouse. Both ends of the greenhouse have half of the bench positioned by the wall while three remaining full benches were positioned at equal distances from each other. Figure 4 schematically displays the distances between the benches.

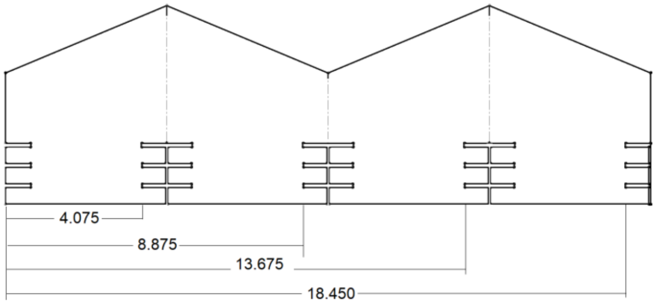

Figure 4 Positioning of Benches in greenhouse (distances shown in meters)

RESULTS

Initial simulations were run to confirm whether the prism layer mesh contains sufficient cells. This was achieved by monitoring the y+ values. Y+ values obtained were typically between 1 and 5; since all y+ wall treatment was used these values are considered acceptable. The numerical temperature and normalised velocity profiles obtained for the first two spans of the greenhouse were compared to that from the original articles for validation purposes. Figure 5 shows the graph of temperature difference (between inside and outside air) as a function of width at a height of 1 m for the spans containing benches. Figure 5 shows the same graph extracted from the original article for comparison purposes. It is evident from Figure 5 and Figure 6 that there is a slight difference in the temperature distribution at plant level. This can be attributed to a number of assumed factors – such as the bench length and position, as well as the size of the roof ventilators. **Figure 7** shows the graph of numerical air velocity normalised by the reference wind speed at 6m (1.4 m/s) as a function of width at a height of 1 m for the spans containing benches. It is evident from Figure 7 and Figure 8 that the velocity distributions show the same trend as the values are seen to gradually increase and reach a peak value at approximately 7.2m from the windward side. A significant drop in velocity is then observed (between the benches), after which the velocity and increases again to a peak value of approximately 0.25 m/s in the original greenhouse and 0.27m/s in the newly created greenhouse simulation. Once again, the slight differences can be attributed to the assumed factors. The velocity contours for the new simulation are shown in Figure 9, and compared to the velocity contours from the results found in the literature (Figure 10). The flow patterns are clearly similar. Air enters the greenhouse at the second roof ventilator, and moves down toward the benches where it splits in two directions. Some of the flow moves toward the right above bench, and forms an anti-clockwise convective cell above the second bench. The rest of the flow moves over the first bench and exits the greenhouse at the first roof ventilator. Confidence has thus been established in the new numerical model.

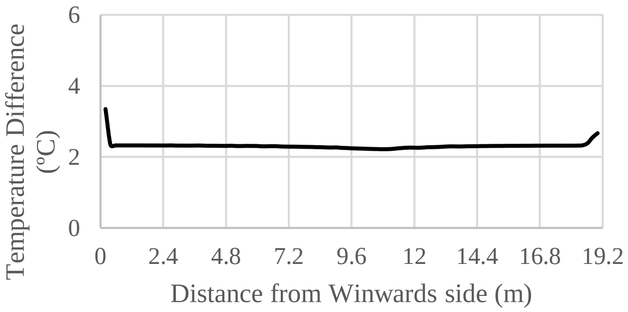

Figure 5 Temperature difference as a function of width at a height of 1 m from original article

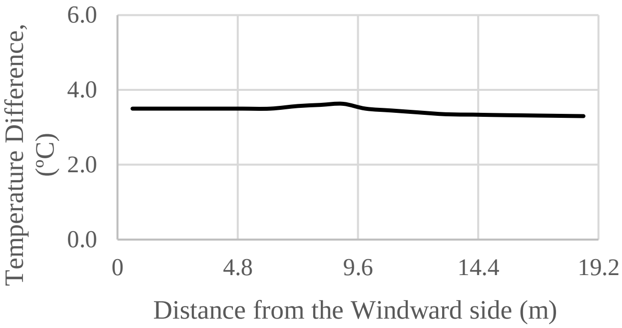

Figure 6 Temperature difference as a function of width at a height of 1 m (Original Greenhouse)

The original greenhouse containing two benches was modified to contain stacked benches as shown in Figure 4. The velocity and temperature contour plots for the latter greenhouse can be seen in Figure 11 and Figure 12 respectively. The temperature contour plot indicates slightly warmer regions at the benches adjacent to the walls. A cooler region is noticed in the center of the greenhouse. The velocity contour plot shows a stream of high velocity air entering the greenhouse at the second roof ventilator, and splitting right above the 3rd benches from the left side. All the air around the benches seems to be relatively stagnant, especially the air underneath the bottom shelves. This can also be seen from the vector plot (Figure 13). To gain further insight a temperature scalar plot has been superimposed on a vector plot where the vectors have a constant length (Figure 14). The air entering the greenhouse is cool compared to the rest of the greenhouse. The cold entering air is spread over the second and fourth stacked benches, and the air is heated by the floor as it moves upward against the walls. The bottom shelve on the right side of the bench (3rd bench) is also cooler compared to the rest of the benches.

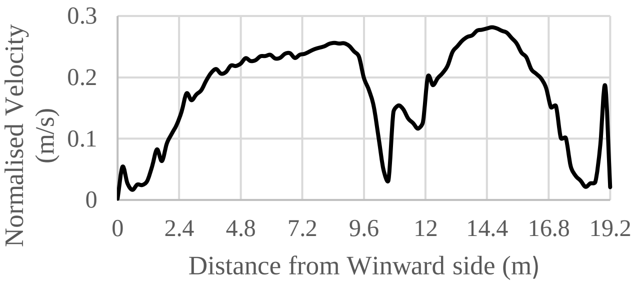

Figure 7 Average air velocity as a function of width at a height of 1m.

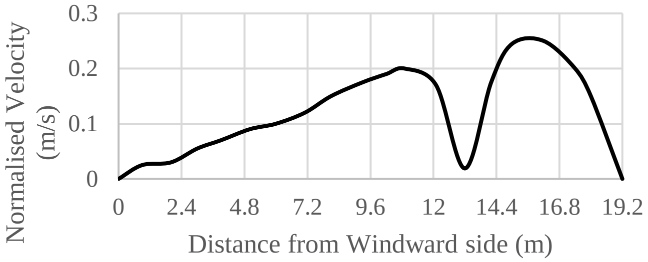

Figure 8 Average air velocity as a function of width at a height of 1 m (Original Greenhouse)

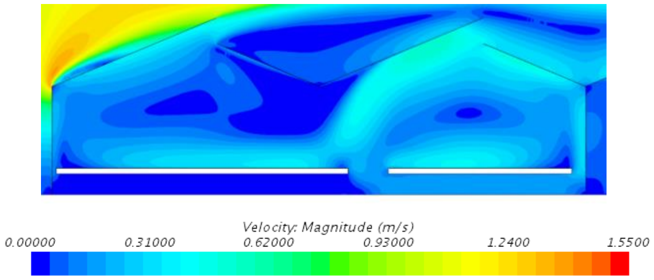

Figure 9 Velocity Contour Plot

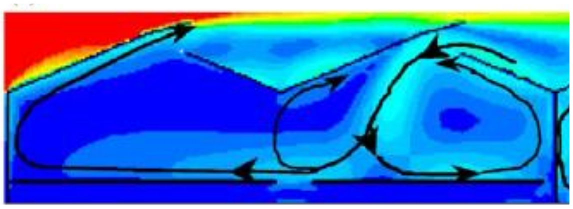

Figure 10 Velocity contour plot (Original Greenhouse - Ould Khaoua)

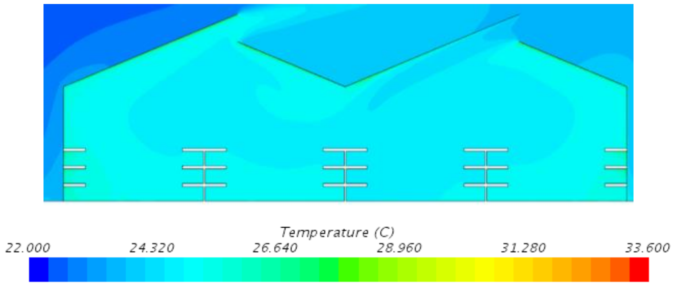

Figure 11 Temperature Contour Stacked benches

Line probes were created in the simulation at different heights to investigate the temperature and velocity distributions further. A numerical line probe was inserted 50mm above each shelve. The bottom line probe is the same height as the line probe inserted in the original greenhouse.

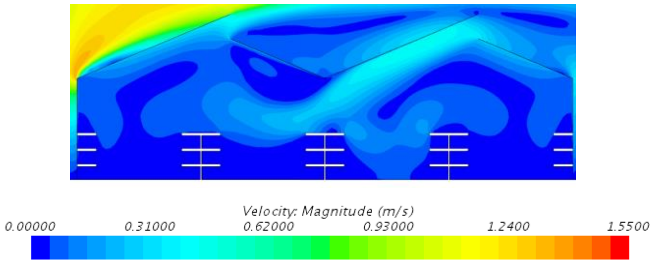

Figure 12 Velocity Contour Stacked benches

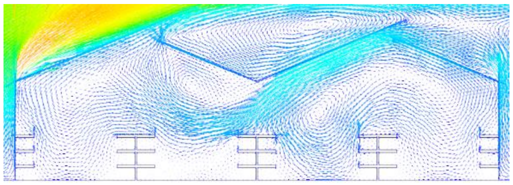

Figure 13 Vector plot stacked benches

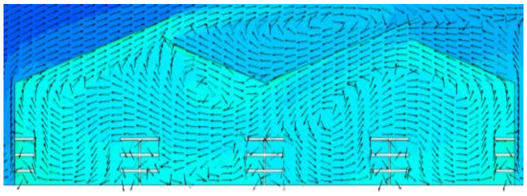

Figure 14 Vector plot superimposed on temperature scalar plot

The temperature distribution plot (Figure 15) shows a homogenous temperature distribution for all three heights, although a slight dip can be seen at approximately 9.4m from the windward side. This corresponds the top shelve of the centre bench arrangement, where the flow from the roof ventilator splits in two opposite directions. Steep gradients were also noticed as expected against the walls of the greenhouse. A minimum temperature of approximately 24.5ºC is reached on the top shelve. When these temperature distributions are compared to the temperature distribution 50mm above the shelves in the original greenhouse, it can be seen that the temperature distribution is not significantly influenced by the type of benches present in the greenhouse, except right against the walls. Temperatures are in general slightly lower for the original greenhouse, where an average temperature of 24.5ºC was observed compared to an average of 25ºC for above the bottom shelve. The velocity distribution is shown in Figure 16. The velocity is on average quite low underneath the bottom shelve, with a maximum velocity of 0.07m/s reached at 11.9m. These regions coincide with the stagnation regions seen in the velocity contour plot. The top shelve exhibits a heterogeneous velocity distribution, with velocities ranging from close to zero against the left wall and at 10m, to a maximum of 0.2m/s reached just before the second set of benches.

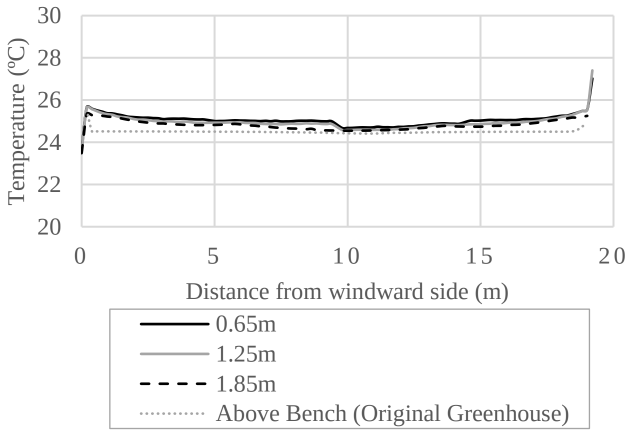

Figure 15 Temperature distribution across shelves at three different heights

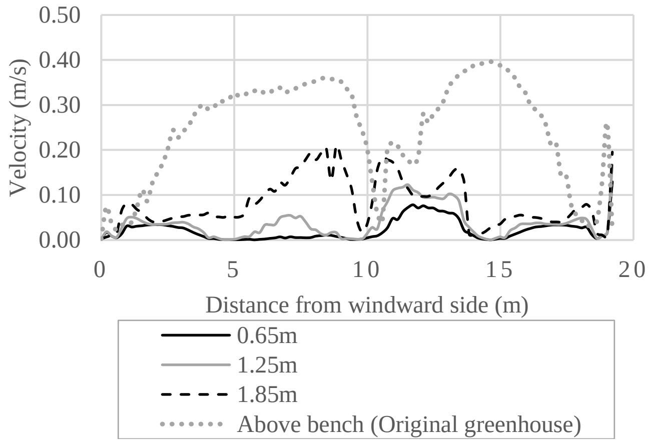

Figure 16 Velocity distribution across shelves at three different heights

The velocities in the original greenhouse are significantly higher compared to the velocities in the greenhouse containing the stacked benches. A maximum velocity of 0.4m/s was reached in the original greenhouse, whereas a maximum velocity on the top shelve of 0.2m/s is found in the greenhouse containing the stacked benches. A steep velocity gradient was noticed as expected for both greenhouses adjacent to the right wall.

CONCLUSION

The effect of stacked benches on the indoor climate of a two-span greenhouse was investigated. Initially, the simulation was successfully validated against the data found in the literature when contour plots and velocity distributions were compared. Discrepancies in the results could be attributed to the assumed length of the ventilators and benches. This validated numerical model was then modified to include stacked benches. The same conditions and mesh parameters were used for simulation of the greenhouse with stacked type benches. From the results obtained, the temperature distributions seem to be almost unaffected from the type of benches, as the temperatures in the original greenhouse were only slightly lower when measured 50mm above the bench. However, the presence of additional racks above significantly lowers the velocities above the bottom racks. This indicates that care should be taken when plants are placed in the lower racks as the velocity could be too low and prevent optimum growth. Growth requirements of the plants are therefore to be considered prior to being positioned on the benches. The shelves adjacent to the walls of the greenhouse experience higher temperatures compared to the rest of the greenhouse. This could also lead to uneven crop yield. The obtained simulation results indicate that the type of benches utilized in a greenhouse could have a significant influence of the growth of the plants placed on the benches. CFD has again been shown as a useful tool in the designing and developing of greenhouse models. Recommendations for future research in this field may include conducting simulations where the greenhouse contains side ventilators, and different roof ventilator configurations.

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