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CFD Investigation on Key Design Parameters of a Hoop-Type Greenhouse

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ABSTRACT

Many blueberry farmers use an open-sided hoop-type greenhouse to enhance agricultural output. A common problem in multi-span greenhouses is the loss of ventilation that scales with the increase in span number. This paper examines the effects of reducing the greenhouse height and adding covers to the formerly open sides in a two-span greenhouse to understand better flow characteristics that may contribute to energy loss. It concludes that lowered height can create a more even temperature distribution, while side covers make the flow direction more predictable but decrease flow speed and increase internal temperature. This paper recommends adding side covers with controllable height to the greenhouse to increase the temperature during cooler periods of the day.

1. Introduction

Many different greenhouse designs exist, each better suited to its own application. Six basic shapes often reviewed are Even Span, Uneven span, Vinery, Arch, Modified Arch, and Quonset. When used well, greenhouses can be a sustainable step towards the second goal of the United Nations development plan - the elimination of world hunger [1]. A farm in Bundaberg uses a multi-span arch greenhouse design, which allows full open ventilation from all sides. This approach, combined with a good covering, can alter greenhouse conditions with minimal active components; testing done in 2019 [2], shows that the centre of a two-span greenhouse is, on average, 0.3 degrees Celsius warmer and 0.3% dryer (RH), while even more changes can be expected as the span count increases [3].

A greenhouse can increase production 5-10 times compared to conventional methods. Therefore, many growers prefer greenhouses. The micro-climate of a greenhouse has an enormous impact on plant growth, and a greenhouse with improperly managed atmospheric conditions will never operate at its full potential. However, when many greenhouses are combined to have economic operations, heat build-up results in unsuitable conditions in terms of temperature. This happens because the single greenhouse has proper air ventilation and is surrounded by air. When the span is more than two, the airflow patterns are affected and negatively impact the subsequent stages. This stifled ventilation makes temperature less controlled by ventilation, and high temperatures can reduce the

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output of a greenhouse [4]. This paper aims to study the effect of different design modifications on the microclimate and suggest structural changes that can bring suitable conditions in the combined greenhouses.

The literature review provides insight into the ideal conditions for the growth of berries; however, many assumptions are made due to a noted variability between different plants. Some studies show a temperature of 20oC is ideal for plants' growth [4,5,6]. However, the growth of fruit has shown to have much more variation, with tests on three different types of grapes turning results of 25 ^{o}C, 35 ^{o}C, and 40 ^{o}C [7]. By noting averages in values and focusing on studies that look at blueberries (a common crop at the sample farm), a value of 30±3oC is assumed as an ideal temperature for berry growth [8].

Computational Fluid Dynamics (CFD) encompasses a range of numerical methods and equations that allow fluid flows to be simulated [9-14]. CFD Modelling using ANSYS Fluent is the most common method for simulating greenhouses with reliable accuracy [3,15-16]. With sufficient data on internal conditions, researchers using CFD modelling have been able to accurately model greenhouses to high enough accuracy to optimize water use [17]. Similar accuracy cannot be reached within the bounds of this experiment, as the location being modelled, timeframe, and author proficiency do not allow for all the tests that might be needed to find every value for an accurate model.

The contents of greenhouse space can significantly affect the CFD analysis, while greenhouse modelling must consider the plant's transpiration. It has been found that transpiration can be measured as a mass/heat exchange with the surroundings, and if humidity is ignored for the model, then CFD analysis can model transpiration as heat flux [17]. By assuming that all water fed to the plant evaporated, the basis for the cooling of the plants was formed. Other research on Rubus plants (sharing the same family as raspberries) found that transpiration drops to 5-15% of daytime rates at night, so the heat flux can be modelled as a sine wave wherein the lowest point is a percentage of the highest, and total cooling throughout the day is based on the amount of water used [18].

2. Methodology

At first, a geometric model is developed using Autodesk Inventor and exported into ANSYS Fluent, the most common software used to model greenhouse micro-climates [3]. To model this accurately, parameters such as wind speed, direction, and temperature must all be known. Temperature, both of wind flow and inside the greenhouse (for comparison) was collected in a minute-by-minute experiment over two weeks [2].

The use of ANSYS fluent is central to this analysis and a common standard program in similar greenhouse studies [17]. One of the reasons this is the case is because of the many parts of the greenhouse modelling which are automatically performed by the program: the solar calculator can be used to accurately map the effect of solar heating, and an attached database can be used to show the thermal properties of the various materials in the model. Trees are frequently used as windbreakers on farms, as they are strong enough to stop the wind, flexible enough to stay standing in rough conditions, and more self-maintaining than manmade structures. Many ANSYS models including plants model the wind flow disruption as a porous media, which calculates flow resistance based on three parameters: viscous resistance, inertial resistance, and porosity.

Research in the general shape of raspberry leaves (treating as individual particles in the porous media) finds a 70 mm long, 40 mm wide leaf [19], with a presumed thickness of ~500 µm [20]. The most applicable study on plant cover porosity gave a porosity value of 0.91. by using this together, along with the effective diameter providing the most resistance, the porous properties are based on research into the average sizes and packing density of the leaves, combined with equations provided by ANSYS to calculate viscous and inertial resistance [21].

Figure 1 shows the 3D model developed in the 3D modelling platform Inventor. This was developed as per the measured dimensions of the existing greenhouse.

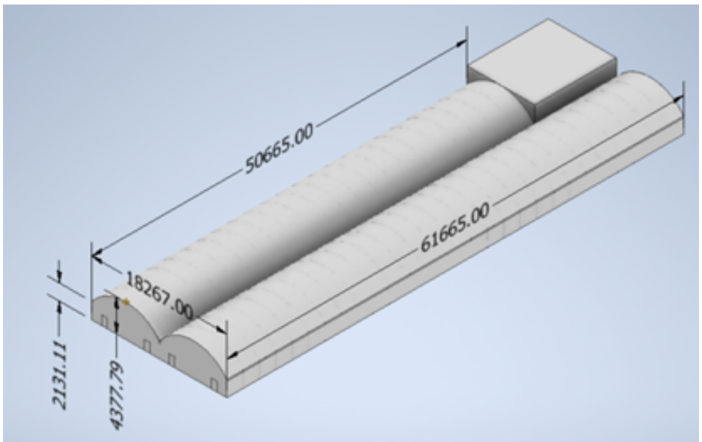


Fig. 1. Physical model used for simulations

This model offers the benefit in the design of making it easy to adjust the greenhouse and side cover height for analysis. The basic design has a cover with a length of 120 mm, which future models can extend, as well as move the roof up and down to affect the inlet size. ANSYS allows the use of adaptive meshing, which refines the mesh in low-quality areas. Settings used are maximum resolution as high as it will go, tetrahedral mesh, defeaturing anything smaller than 5 mm (which prevents over-meshing in the 1 mm lip separating the cover and inlet zone) and setting the target skewness to 0.4. This creates the mesh in figure 2, with 45895 nodes and 210489 elements.

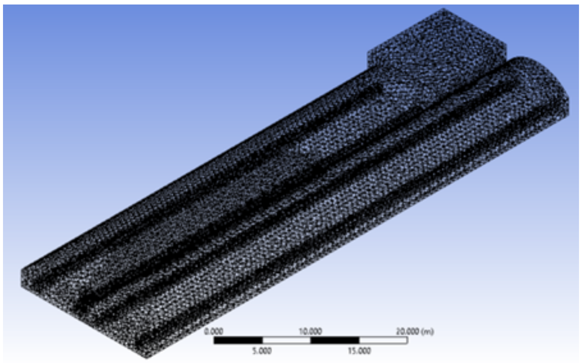


Fig. 2. Mesh of model

The orientation of the greenhouse is selected based on an actual greenhouse in Bundaberg. By taking the plant row size and assuming that each plant is watered with 30 ml/day (based on correspondence with the farm), the average cooling can be found based on the number of plants in the row and then expanded into a sine wave of heat flux (kW/m^2) where the minimum flux is a fraction of the maximum, and the wave equated to the thermal energy needed to evaporate 30 mL/day·plant. The model has only fluid sections, but faces can be designated as walls to create solid results; the roof is a 0.2 mm thick plastic wall, while the bottom is a 1 m thick dirt layer for the ground. Figure 3 shows the finished model: blue for inlets, red for outlets (where air can only escape), grey for walls, and yellow for a symmetry plane.

The general setup of the model (established in ANSYS) is to calculate energy and viscosity, with viscous modelling set to k-epsilon realizable and the solar calculator equipped with the location, orientation, and time of the model. Conditions are initialized to improve early accuracy, and the simulation is run for 600 six-second timesteps (1 hour total).

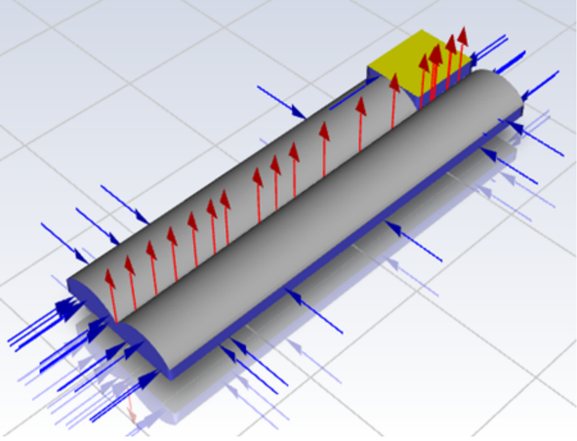


Fig. 3. Model Boundary Conditions

The results are analyzed in several ways using ANSYS post-processing, all of which can be seen in Figure 4. The first is a five-point method: four points are placed in the same locations as temperature probes used by [2], and a fifth is placed in the plant zone shown to be the hottest in most simulations. These can be used to compare the original and new model, and to analyze the effect of changes on the temperature in the plant area. The next is with contour planes; one covers the plane the temperature probes are arranged in, while the other two run the length of the middle of the greenhouse. Finally, particle tracking on both the probe plane and the entire simulation body can be used to track how wind flows within the boundaries of the simulation.

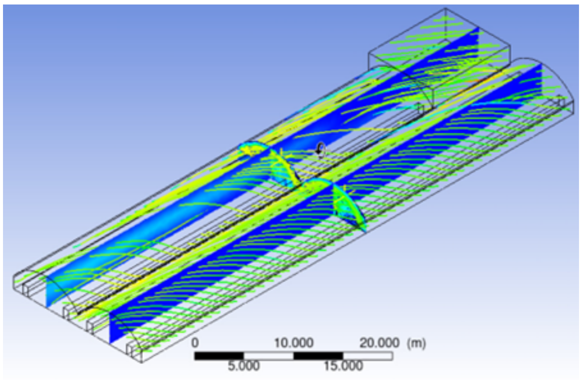


Fig. 4. Post-processing analysis tools

3. Results

The simulated model displays slightly different temperature characteristics from the data taken from the previous model [2]. Dutta's results show variation between two points on either of the greenhouse, each vertically displaced and located around the centre of the length, of up to 1oC, and an initial downward trend in temperature as the greenhouse cools. Throughout the entire 1-hour runtime, the temperature between points does not greatly diverge, which is theorized to be a result of how closely cropped the model's borders are with the greenhouse zone, where more realistic models must account for airflow in the area surrounding the greenhouse. However, the model can be considered accurate, as the model varied from experimental results by 0.22% or less at all times.

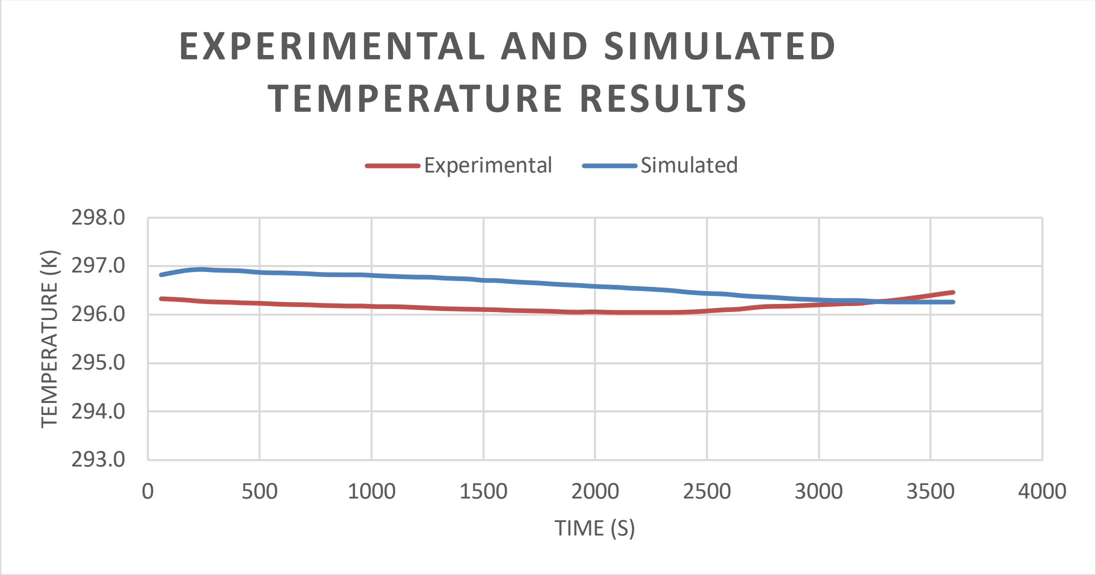


Fig. 5. Comparison of greenhouse temperature results in simulated and experimental models

3.1 Base Model Flow

The wind flow for the base model is easy to identify wind entering through the inlet is forced into the roof by a high-pressure zone, then curves along the roof, back down in the centre, and back into the roof again before exiting, as shown in Figure 6. This creates three distinct low-pressure swirls (which have the appearance of a spiral in the 3D view of airflow): two are between the rows of plants, while the third resides on one side of the roof and most likely changes sides depending on the wind's entry direction.

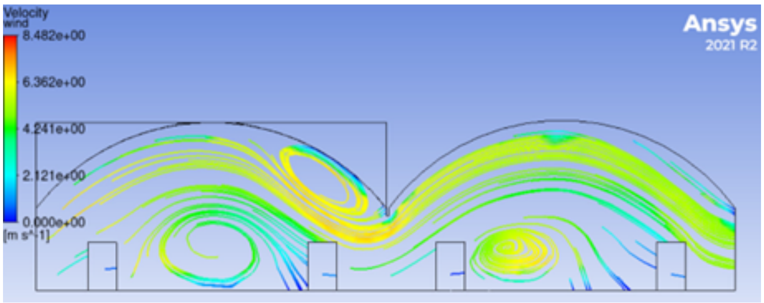
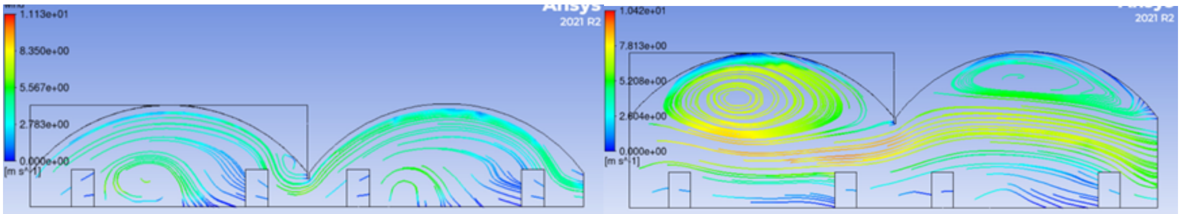


Fig. 6. Fluid flow profile of the base model

Very few tracked particles in the model pass through the porous plant zone, indicating that wind flow is very stagnant within the plant space. The particle tracker frequently stopping at the boundary of the plant zone indicates that flow is simply so stagnated that the path is not shown. A more advanced model would most likely need to account for the plants not forming an unbroken row, requiring one row for the greenhouse heat mat (the lower half of the plant row) and one set of bodies to indicate each plant.

3.2 Height Change

The first modification is changing the inlet size by reducing the greenhouse height, which produced interesting interactions with the low-pressure spiral flow seen in the base model, as seen in figure 7. Reducing the height reduces velocity all around the model, reducing the size and speed of the roof-attached spiral and compressing the ground spirals. Increasing the height increases the size of vortexes in the roof area but allows the flow to pass through the plant area with less disturbance. The average temperature in the plant data point is also shown to decrease at lower heights and increase with taller structures, likely due to the lower heights forcing airflow towards the centre plant rows.

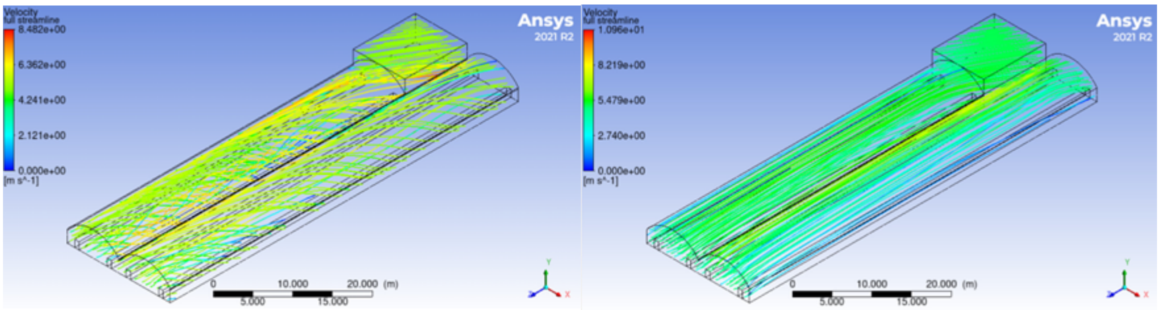


(a) (b)

Fig. 7. Height Change wind flow profile: 1-meter reduction (a) and 1-meter increase (b)

3.3 Side Cover Model

The second variation is changing the inlet profile by adding covers to the side of the greenhouse, which gives an easier to predict but less ventilated design. The addition of side covers of any height dramatically reduces the wind speed in the entire model, especially at the plant layer, as shown in figure 8. Since the wind must pass alongside the plants for the entire length, it loses speed as it passes the entire distance. This is partially negated by the aforementioned issue of a forcibly maintained exit speed. In the case of this model, it would be like placing a ventilation fan at the back of the greenhouse to force air out.



(a) (b)

Fig. 8. Side Cover 3D streamline: Standard side cover (a) and full-length side cover (b)

4. Conclusions

A CFD model of the selected greenhouse was developed, and its temperature characteristics is compared with the experimental data, which shows good agreement. From these simulations, it can be concluded that a decreased greenhouse height leads to lower wind speeds and more turbulence at the height of the plants. This more evenly cools each plant. Additionally, side covers on the greenhouse can control the direction of airflow but will decrease the flow speed, and full coverage on the sides leads to a jump in temperature.

Since the experimental temperature of the greenhouse was found to be much lower than the desired 30±3°C from the literature review, a taller greenhouse with side covers should be based on the findings of this report, presenting a better set of growing conditions. The simulation time was earlier in the year and was nnd not in the summer heat, so the design must be adjustable for hotter periods. Overall, should the greenhouse be consistently maintained within the desired range, research indicates that growth increases linearly with warmth up to an ideal temperature before linearly declining beyond it [8]. Hence, an effort needs to be made to control the temperature consistently. Side covers are easier to alter than height, in this case, and have had the biggest impact on temperature in the simulations, so side covers designed to lower when the greenhouse is too cold, and raise when it is too hot, may improve the design.

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